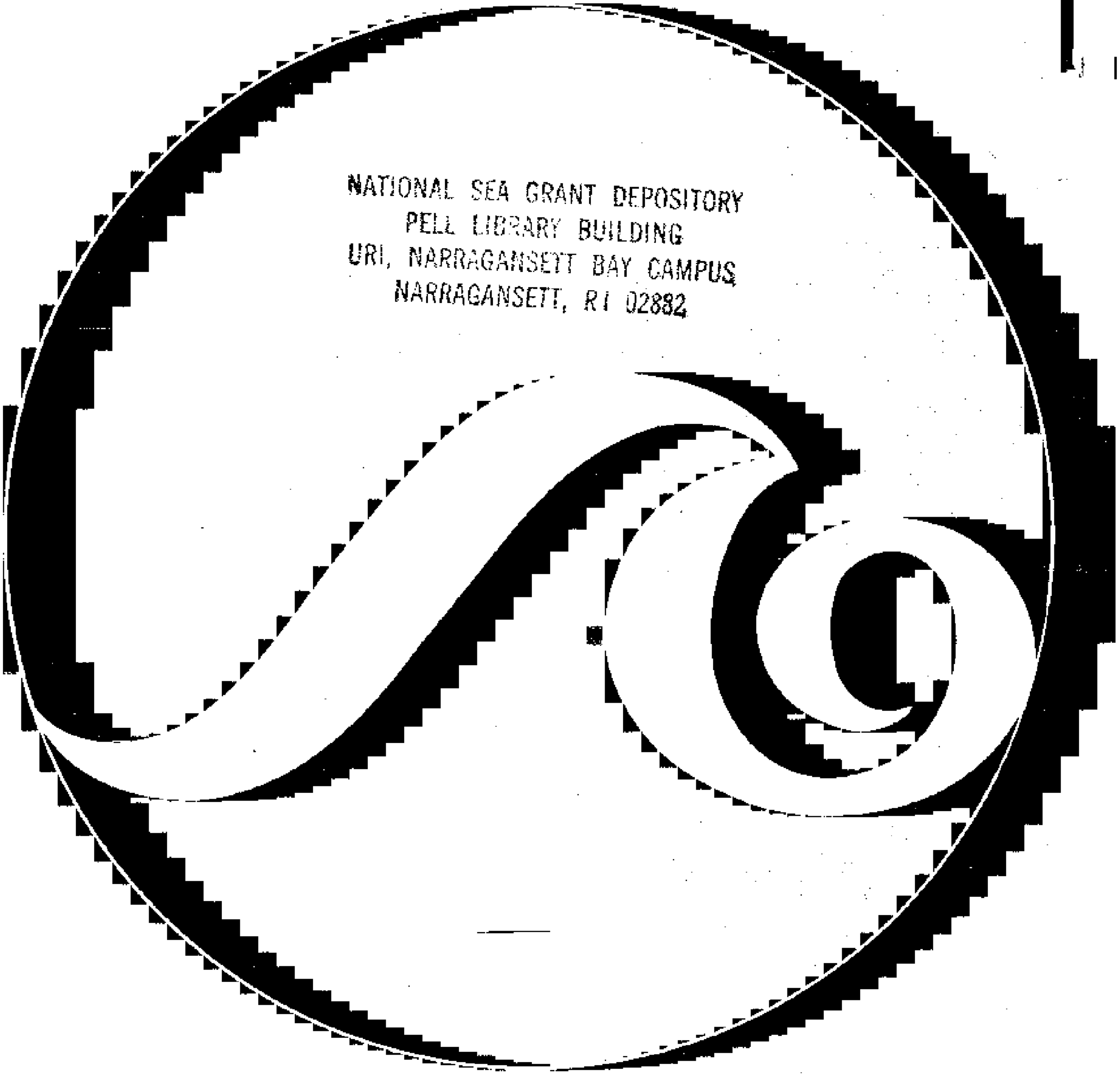
Koichi Masubuchi

Development of Joining and Cutting Techniques for Deep-Sea Applications



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DEVELOPMENT OF JOINING AND CUTTING TECHNIQUES FOR DEEP-SEA APPLICATIONS

BY

Koichi Masubuchi

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ABSTRACT

This is the final report of a four-year research program entitled "Development of Joining and Cutting Techniques for Deep-Sea Applications". The objective of this research program from July 1, 1976 through June 30, 1980 was (1) to generate basic information pertinent to joining and cutting techiques for deep-sea applications and (2) to develop some prototype tools suitable for underwater joining and cutting for deep-sea applications. The program covered the following tasks:

Task 1: Evaluation of various joining and cutting techniques for deep-sea applications

Task 2: Construction of a pressure tank (using matching funds)

Task 3: Experiments on arc welding and cutting under simulated deep-sea conditions

Task 4: Continued experiments on arc welding and cutting in deep-sea conditions

Task 5: Design of prototype tools for underwater welding and cutting in deep-sea conditions

Task 6: Test of prototype units under simulated deep-sea conditions

Task 7: Operational characterization of deep-sea construction and repair

Task 8: Preparation of a final report.

The work was performed primarily by a group of graduate students at the Department of Ocean Engineering of M.I.T. as their theses studies under the supervision of Professor Koichi Masubuchi. Since all of these students left M.I.T. this final report is written by Professor Masubuchi who is shown as the sole author of this report.

The objective of Task 1 was to evaluate potential uses of various joining and cutting techniques for deep-sea applications. Factors which were considered in the evaluation include (1) the need for metals joining in the deep-sea, (2) the dependency of potential processes on diving system capability and cost, as well as (3) technical problems inherent to various joining processes when they are used in deep-sea. The results are presented in Chapter 3.

Under Task 2 a pressure tank for welding experiment was built. The tank, 6 feet long and 30 inches in diameter, can be pressurized up to 300psig simulating the water depth of 700 feet. In making a welded

sample, the sample is placed in the tank, the door is closed, and the tank is pressurized. Welding is performed completely automatically by merely pressing an appropriate button. When underwater welding is necessary, specimens to be welded are immersed in water contained in a pan which is placed in the tank.

The objective of Task 3 was to study effects of water pressure on arc welding characteristics and properties of welds. It was demonstrated that the deep-sea underwater simulation facility built under Task 2 works satisfactorily. Welds were made using gas metal-arc and flux-shielded arc processes in dry and wet conditions at pressures up to 300psig which corresponds to 700 feet deep water.

Efforts under Tasks 4 through 7 were made on two joining processes - stud welding and flux-shielded arc welding. Efforts were made to develop integrated and automated welding systems which can be activated by merely pressing a button or which can be remotely activated from a support ship. Since the stud welding is a simple, fully-automated process it was possible to demonstrate that it can be successfully used underwater under pressure. We believe that the best way is to design a water floodable stud welding gun. Some efforts have been made to develop a water floodable stud welding gun.

Efforts also have been made to develop an integrated, fully automated welding machine using the flux-shielded process. A conceptual design of an automatic underwater welding machine which could be used in deep-sea has been developed. A simple automatic welding machine which can be operated by merely pushing a button has been constructed and tested.

ACKNOWLEDGEMENTS

The work, results of which are reported here, was performed primarily by a group of graduate students at the Department of Ocean Engineering of M.I.T. as their theses studies under the supervision of Professor Koichi Masubuchi. Names of these students are:

Jun-ichi Chiba who submitted a thesis for an M.S. degree in May 1977

Chon Liang Tsai who submitted a thesis for a Ph.D. degree in September 1977

Subodh Prasad who submitted a thesis for an M.S. degree in February 1978

David P. Erickson who submitted a thesis for M.S. and Ocean Engineer degrees in May 1978

Osamer Iimura who submitted a thesis for an M.S. degree in May 1978

Toshioki Kataoka who submitted a thesis for an M.S. degree in May 1978

Joseph Lombardi who submitted a thesis for an M.S. degree in May 1980.

This final report is written by Professor Masubuchi, since all of these students left M.I.T.; therefore Professor Masubuchi is shown as the sole author of this report. The author wishes to acknowledge the efforts by these students.

The author also acknowledges assistance given by Anthony J. Zona (Technical Instructor), Hironori Ozaki (Visiting Research Associate), Peter C. Schechter and Roy Y. Nakagawa (Undergraduate Students).

The major portion of the research fund came from the NOAA Office of Sea Grant. Matching funds were provided by a group of companies including Hitachi Shipbuilding and Engineering Co., Ishikawajima Harima Heavy Industries, Kawasaki Heavy Industries, Mitsui Engineering and Shipbuilding Co., Nippor Kokan K.K., and Sumitomo Heavy Machinery Co. Some other companies including Nelson Division of TRW, Inc., KSM Fastening Systems Division of Omark Industries, Atlantic Diving Co., and Taylor Diving and Salvage Co. provided assistance in various forms including loaning equipment, donating materials and giving technical consultations.

RELATED REPORTS

Chon-Liang Tsai, Hironori Ozaki, Arnold P. Moore, Lawrence M. Zanca, Subodh Prasad, and Koichi Masubuchi, DEVELOPMENT OF NEW, IMPROVED TECHNIQUES FOR UNDERWATER WELDING. MITSG 77-9, Massachusetts Institute of Technology, April 1977.

ADVANCES IN UNDERWATER WELDING. The M.I.T./Marine Industry Collegium Opportunity Brief. MITSG 76-8, Massachusetts Institute of Technology, August 1976. 24pp. $2.50

Alan J. Brown, Russell T. Brown, Chon-Liang Tsai, and Koichi Masubuchi. REPORT ON FUNDAMENTAL RESEARCH ON UNDERWATER WELDING. MITSG 74-29. Massachusetts Institute of Technology. September 1974. 282pp. $5.00

Koichi Masubuchi. MATERIALS FOR OCEAN ENGINEERING. M.I.T. Press. February 1970. 542pp. $14.50

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ADMINISTRATIVE STATEMENT

This is the final report of a four-year research program conducted by researchers at the Massachusetts Institute of Technology. The objective of this research program was (1) to generate basic information pertinent to joining and cutting techniques for deep-sea applications and (2) to develop some prototype tools suitable for underwater joining and cutting for deep-sea applications.

During the four-year period which began July 1976, the interest in and enthusiasm about underwater welding and cutting on the part of the ocean engineering and welding industries has grown significantly. There has been an ever increasing demand for developing underwater welding and cutting techniques for deep-sea applications. The publication of this report should therefore be very timely and it should provide useful information to the rapidly expanding ocean engineering industries.

Funds for this research effort came in part from a group of Japanese companies in shipbuilding and heavy industry, the NOAA Office of Sea Grant through grant number NA79AA-D-00101, and the Massachusetts Institute of Technology. Several companies in U.S.A. provided various kinds of assistance, including the loaning of equipment, providing of materials and consultations.

Dean A. Horn
Director

January 1981

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CHAPTER 1

INTRODUCTION

A four-year research program, "Development of Joining and Cutting Techniques for Deep-Sea Applications", was conducted at the Massachusetts Institute of Technology from July 1, 1976 through June 30, 1980. The objectives of this research program were (1) to generate basic information pertinent to joining and cutting techniques for deep-sea applications and (2) to develop some prototype tools suitable for underwater joining and cutting for deep-sea applications. This is the final report of the four-year program.

1.1 M.I.T.'s Research Efforts on Underwater Welding

Since the modest beginning which started in 1968 M.I.T. researchers under the direction of Professor Koichi Masubuchi have conducted systematic research on underwater welding. So far eighteen theses for B.S., M.S., Ocean Engineer and Ph.D. degrees have been prepared. These theses which are listed in Section A of REFERENCES as [T1] through [T18], were prepared while this research program was conducted from July 1976 through June 1980. A number of reports and papers have been published and two U.S. patents have been granted. Names of authors and titles of important publications and patents are listed in Section B of REFERENCES as [P1] through [P19] in the order of their dates of publication.* Details of the two patents are included in APPENDIX A.

M.I.T.'s active involvement in research on underwater welding and cutting began in 1968 when Professor Koichi Masubuchi, an expert on welding fabrication, joined the faculty. In 1970 Professor Masubuchi

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* Section C of REFERENCES lists references which are not related to the M.I.T. studies. They are listed as [C1], [C2], [C3] ......, in the sequence as they are referred to in this report.

published a book entitled Materials for Ocean Engineering which contained as its appendix a state-of-the-art report on underwater welding and cutting [P1]. This textbook was prepared under a grant from the National Sea Grant Office. During the 1970/71 academic year two thesis on underwater welding were prepared [T1,T2,P3]. A research program on underwater thermit welding was conducted for the Office of the Navy Supervisor of Diving, Salvaging, and Ocean Engineering [P2]. Anderssen continued this study during the 1971/72 academic year and wrote a thesis on underwater exothermic welding [T3, P4].

A series of research programs supported by the Office of Sea Grant, NOAA started in July 1971 as shown in Figure 1-1. The first three-year program on "Fundamental Research on Underwater Welding and Cutting" was conducted during the period from July 1, 1971 through June 30, 1974. The program covered the following phases:

Phase 1: A survey of fundamental information on underwater welding and cutting

Phase 2: A survey of heat flow during underwater welding

Phase 3: A study of the mechanisms of metal transfer in underwater welding

Phase 4: A study of the effects of water environments on metallurgical structures and properties of welds

Phase 5: The development of improved underwater welding methods.

A final report was issued in September 1974 [P7].

The second Sea Grant supported program entitled "Development of New, Improved Techniques for Underwater Welding" was initiated in July 1974. It was hoped that with the understanding of the basic mechanism of underwater welding gained from the earlier program the techniques could be further improved. This program was originally conducted at the M.I.T. laboratory, but in the summer of 1976 a series of underwater welding experiments were conducted under actual diving conditions in the Baltic Sea near Travemünde, the Federal Republic of Germany. The Baltic

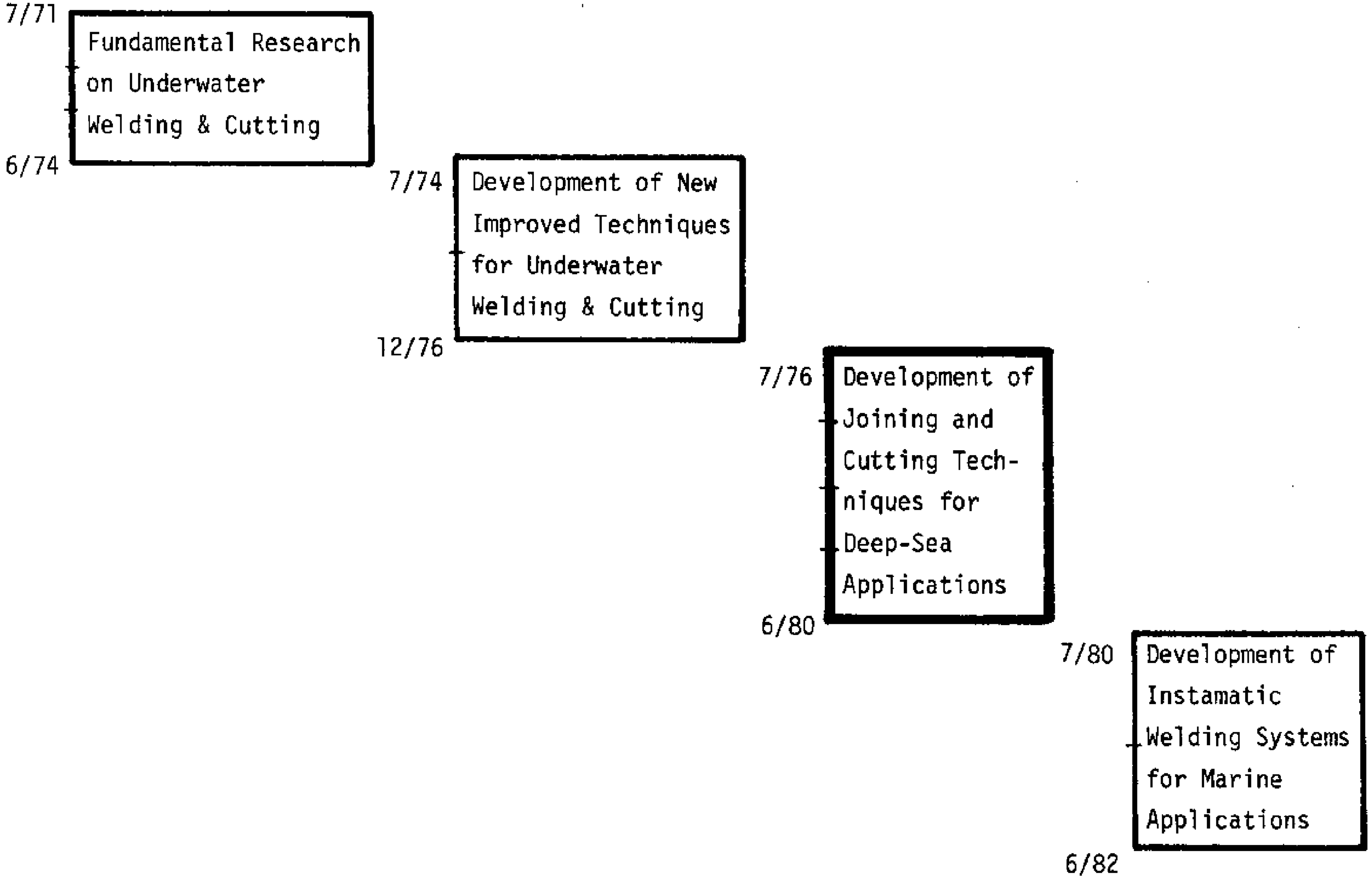


FIGURE 1-1 Development of Sea Grant supported research programs on welding at M.I.T.

Sea welding experiment was conducted as a part of the U.S.-German cooperative effort supported jointly by the Manned Undersea Science and Technology (MUST) Office of NOAA and the Gesselschaft für Kernenergieverwertung in Schifflau und Schiffahvst (GKSS) mbH. Thus the original two-year program was extended for six months until December 1976. This program covered the following phases:

Phase 1: The development of the conceptual designs of several new, improved underwater welding and cutting techniques
  A. The possible uses of various welding and cutting techniques
  B. The improvement of arc welding processes

Phase 2: Further study of one or several of the most promising techniques

Phase 3: Further tests and improvement of tools and/or machines

Phase 4: A study of a total operation systems for underwater welding and cutting

Phase 5: Experiments under the Baltic Sea, as a part of the MUST program, to evaluate several underwater welding processes including shielded metal arc and flux-shielded arc welding processes.

A final report of this research program was issued in April 1977 [P13].

The third Sea Grant supported program entitled "Development of Joining and Cutting Techniques for Deep-Sea Applications" was initiated in July 1976. The original three-year program was extended for another year. This report is a final report of the four-year research program.

The fourth Sea Grant supported program entitled "Development of Fully Automated and Integrated ("Instamatic") Welding Systems for Marine Applications" was initiated in July 1980. The objective of this two-year program is to develop fully automated and integrated welding systems, which may be called "instamatic" welding systems, for various marine applications. These systems, which will be developed through careful engineering, will be able to perform certain prescribed welding jobs by a person with no welding skill. In many cases welding will be performed in a completely enclosed system so that no spark and very little fume will be generated from the welding system. These welding systems can be successfully used for various applications, some of which are listed as follows:

(1) Certain repair jobs on board a ship and salvaging jobs which must be performed when no skilled welder is available

(2) Certain welding jobs which must be performed in a compartment where sparks from the welding may cause fire or explosion

(3) Certain welding jobs which must be performed in hazardous environment making it difficult or impossible for them to be performed by human welders

As is discussed in later parts of this report, the current research effort on instamatic welding systems is a natural extension of the research on deep-sea underwater welding which is covered in this report. In fact, some of the instamatic welding systems can be used with some modifications for underwater applications.

1.2 Growth of the Ocean-Related Industries and Their Interest in Underwater Welding and Cutting

During the last 20 years offshore oil drilling and other ocean-related industries have grown tremendously and they are expected to have continued growth in the future. As the number of ocean engineering structures has increased, there has been a considerable increase in the interest in technologies related to underwater construction, inspection and repair.

Figure 1-1 shows changes of the size of the world fleet of offshore oil drilling rigs since 1960 [C1]. In 1962 there were only 62 offshore oil drilling rigs in the world, but the number increased to 470 in 1978. The figure clearly shows the increase of the production of offshore oil drilling rigs since the oil embargo by the OPEC nations in 1973. Until 1973, the yearly production in the world of offshore oil drilling rigs can be classified into several types including jack-up type, semi-submersible type, ship/barge type and submersible type as shown in Figure 1-2.

Figure 1-3 shows areas where these offshore oil drilling rigs were used in 1977 [C1]. The United States, primarily the Gulf of Mexico and Alaska, and the North Sea represent major areas where these rigs operated.

Although most of the actual offshore oil production comes from waters less than 400 feet deep, exploratory drilling has been conducted in water depths greater than 3,000 feet as shown in Figure 1-4 [T16,C2]. It is now estimated that the area from the shore to a water depth of 200 meters (660 feet) probably contains from 55 to 70% of the potential reserves of offshore petroleum and the area between 200 meters to 2,500 meters (8,200 feet) water depth from 20 to 35% [T16,C3]. From this estimate, it is clear that drilling and production will go into deeper and deeper waters as the development of offshore oil fields expands. This will be achieved by a higher level of technical advance in drilling and production systems and the development of related offshore and underwater structures [T16].

Although offshore oil drilling rigs represent major ocean engineering structures in operation today, many other structures for various applications are being built or considered. They include structures for ocean bottom mining, ocean exploration, ocean energy conversion, salvaging etc. As the number of ocean engineering structures increases there is an increased demand for underwater construction, inspection and repair of these structures. Some construction works need to be performed on site underwater. For example, some very large structures may need to be joined underwater. Some ocean structures which are very difficult or

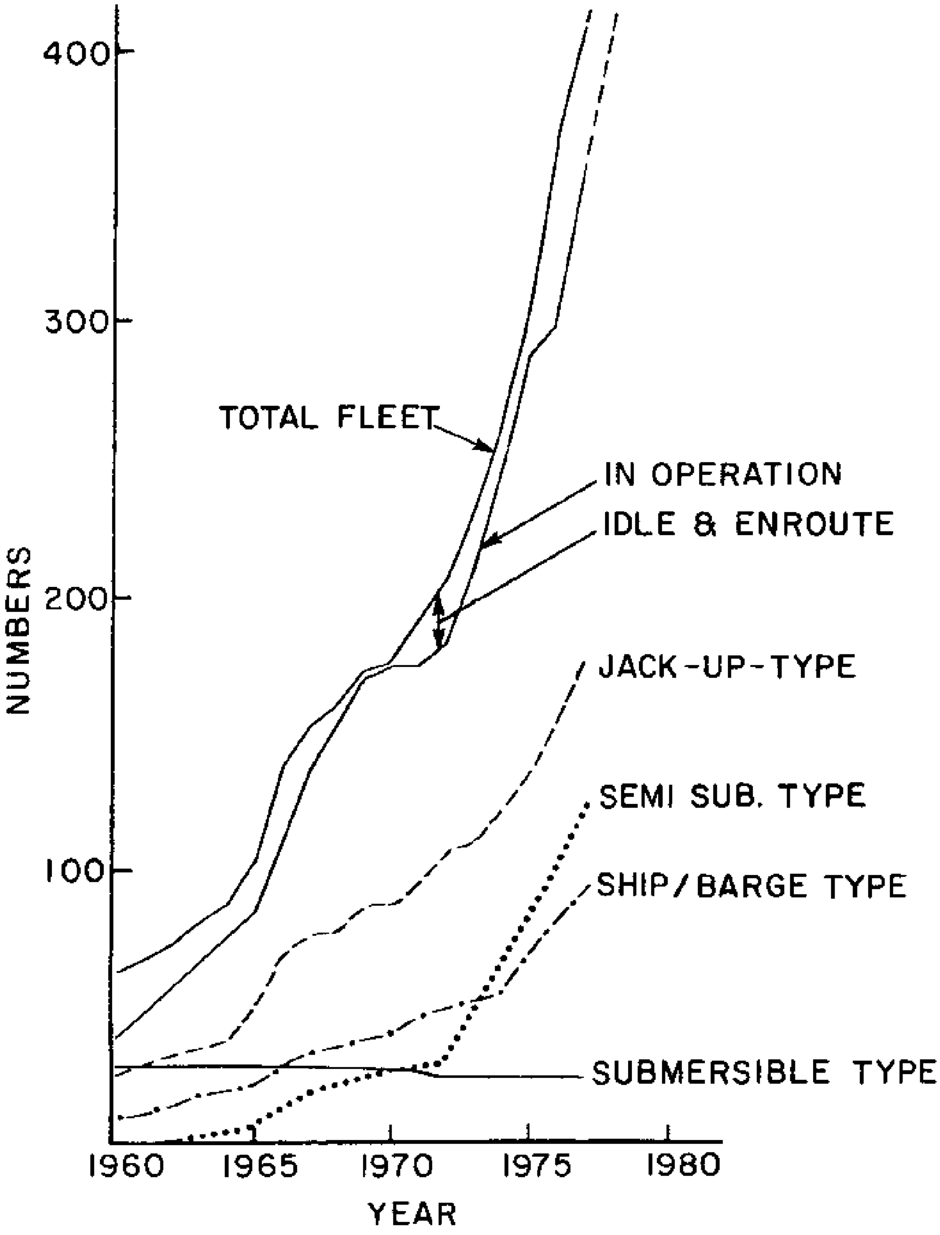


FIGURE 1-2 Changes of the size of the work fleet of offshore oil drilling rigs [c 1]

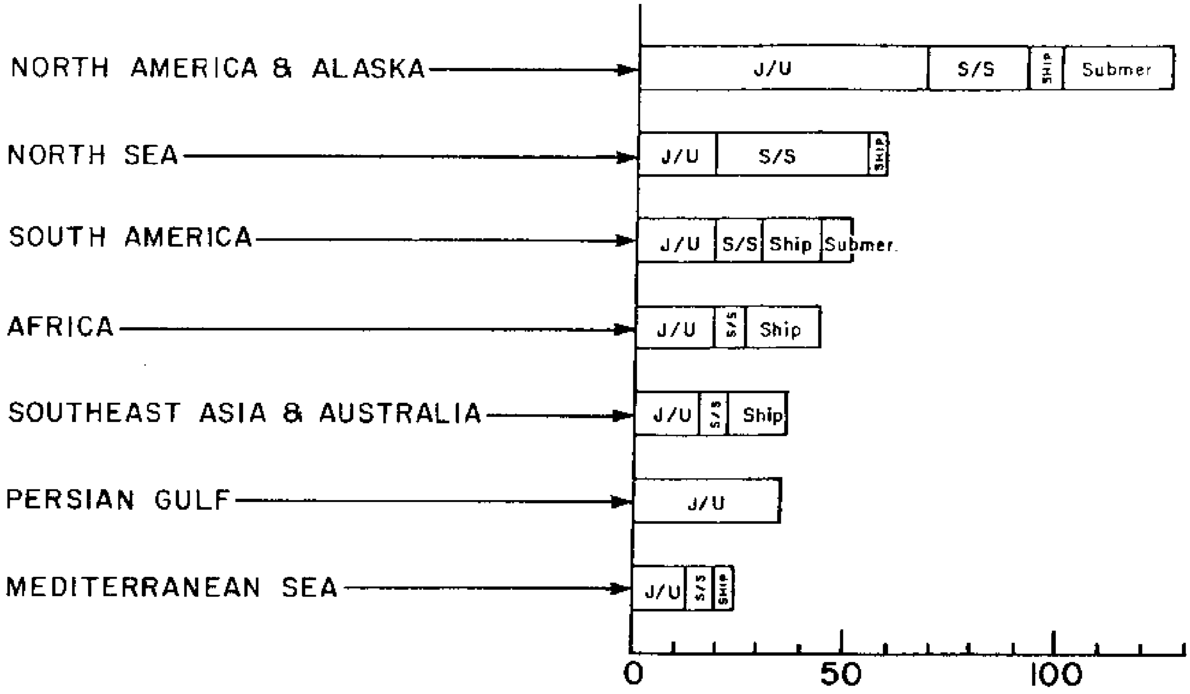


FIGURE 1-3 Areas of operations in 1977 of offshore oil drilling rigs [C1]

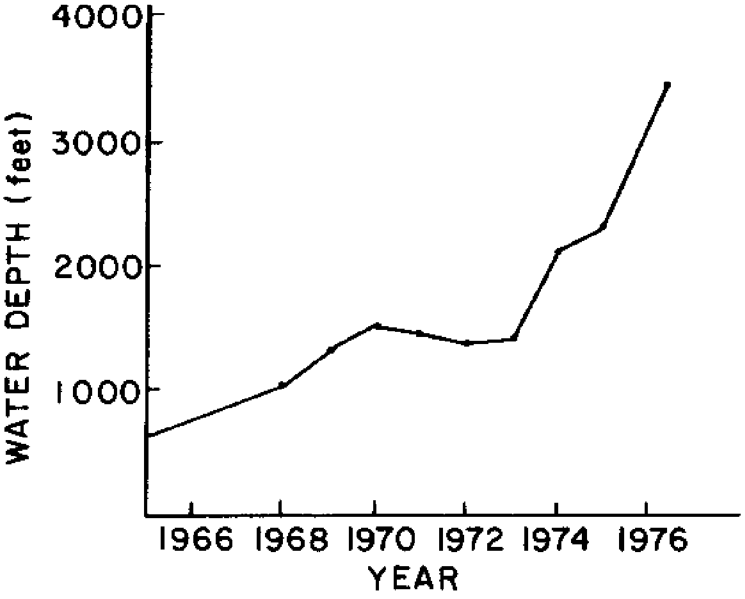


FIGURE 1-4 Water depth records for offshore drilling operations [T16, C2]

impossible to move to dry docks must be inspected and repaired on site.

It is interesting to note that there is a two-way relationship between the demand for new and improved technologies and their potential uses. The new and/or increased demand causes improvement of existing technologies and even development of new technologies. At the same time new and/or improved technologies create increased or even new markets for these new and/or improved technologies. For example, underwater inspection and repair technologies, including welding and cutting technologies, have been improved considerably during the last several years due largely to the demand for inspection and repair of offshore structures. Now people are considering using these technologies for some inspection and repair jobs of ships while they are afloat instead of putting them in dry docks.

1.3 Development of Underwater Welding Technology

Underwater welding, as the name implies, is "welding produced underwater". Difficulties associated with underwater welding have been experienced since the early 1900's [P12]. Underwater welds are plagued by a rapid quenching effect from surrounding water and a susceptibility to hydrogen embrittlement. Underwater welds tend to have less ductility compared to similar welds made in air. Actual welding operations must be performed in a hazardous environment with limited visibility and mobility. Therefore, applications of underwater welding have been limited, until recently, to temporary repairs or salvaging operations.

To meet the increased demand for the construction and repair of offshore oil drilling rigs and other structures the technology of underwater welding has advanced significantly during the last decade and its applications have increased considerably. The needs for underwater welding may be classified into the following categories [P13]:

Category 1: Underwater construction and repair of some critical structures including pipelines

Category 2: Permanent repair of underwater structures including offshore oil drilling rigs

Category 3: Emergency repairs of structures including the rescue and salvage of sunken ships

Underwater welding is also used for repairs of some nuclear reactor components which are immersed in water. However, this subject is considered to be outside the scope of this report.

Underwater construction and repair in Category 1 require high quality welds comparable to those made in air and the expensive dry chamber system may still be the answer. Permanent repairs (Category 2) can be done using a reliable wet shielded metal arc process or, if better quality is needed, an arc welding process using a movable dry chamber. Emergency repairs (Category 3) can be made by various processes including the wet shielded metal arc process which is currently most widely used at least in shallow sea applications.

Offshore platforms have traditionally been fabricated on land, towed to the site, and submerged into place, a procedure that is risky and that severely limits the size and geometric complexity of the structure. If the appropriate underwater techniques become available, sub-assemblies of convenient size and shape could be prefabricated on shore and assembled at the site.

The conventional methods of laying offshore pipelines have become increasingly expensive as the distance from the shore, the water depth, or the pipe diameter increases. The appropriate underwater techniques could bring down these costs.

Dry-dock time is expensive and ship repairs could be done for much less cost if the appropriate underwater techniques become available and if "code-quality" welds could be made underwater.

Current underwater welding technology can produce "code-quality" welds when a dry chamber system is used. But the large pressurized air, or inert gas, chambers used to exclude water from the work area require extremely high operational cost which can not be afforded for many applications. But the economically affordable wet process produces welds of an inferior quality. A critical issue is how much weld quality can be achieved with how much cost. Many research and development efforts have been made, and are still being made, to develop techniques of joining metals underwater which can produce welds of high quality at reasonable costs. The ocean-oriented industries have indicated their overwhelming interest in the development of the underwater welding technology.

One clear indication of this interest is the recent surge of publications on underwater welding. The M.I.T. Sea Grant report published in 1977 [P17] includes in its appendix a bibliography of underwater welding literature published in the world since 1930. Figure 1-5 shows the numer of articles on underwater welding published each year since 1930. The figure clearly shows sudden increases in papers on underwater welding since around 1960. Although no special effort was made during this research program to survey articles on underwater welding published during the last few years, it is believed that the number of articles on underwater welding is still increasing.

As an indicator to show how the industry and professional societies have become increasingly interested in underwater welding it may be worth mentioning the following activities. In 1974 the American Welding Society established the D3b Subcommittee on Underwater Welding of which the major task is to develop the first specifications on underwater welding [C4]. In 1977 the International Institute of Welding formed the Select Committee on Underwater Welding. One of their objectives is to develop standards on underwater welding which may be adopted by welding societies in various countries. In April 1979 the Department of the Navy, Naval Sea Systems Command issued a revised technical manual on underwater cutting and welding [C5].

In 1976 a final report on Underwater Electrical Safety Practices was published by the Marine Board of the National Research Council [C6].

The major subject covered in this report is the safety of welders from electrical hazards during underwater welding.

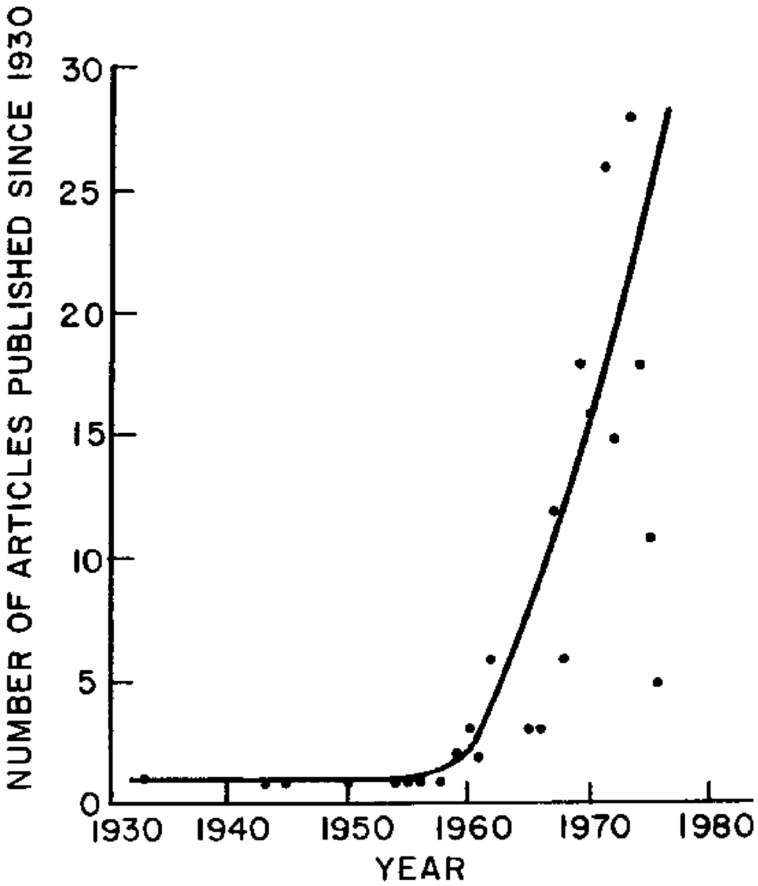


FIGURE 1-5 Articles on underwater welding published since 1930. [P12]

CHAPTER 2

SCHEDULE AND RESEARCH PERFORMANCE

The research program, which was carried out from July 1, 1976 through June 30, 1980, covered the following tasks:

Task 1: Evaluation of various joining and cutting techniques for deep-sea applications

Task 2: Construction of a pressure tank (using matching funds)

Task 3: Experiments on arc welding and cutting under simulated deep-sea conditions

Task 4: Continued experiments on arc welding and cutting in deep-sea conditions

Task 5: Design of prototype tools for underwater welding and cutting in deep-sea conditions

Task 6: Test of prototype units under simulated deep-sea conditions

Task 7: Operational characterization of deep-sea construction and repair

Task 8: Preparation of a final report.

Tasks 1 and 2 were carried out during the first year (July 1976 - June 1977). Tasks 3, 4, 5, and an initial work of Task 6 were conducted during the second year through June 1978. Efforts during the third year involved Task 6. Efforts during the fourth year involved the remaining work of Task 6, as well as Tasks 7 and 8.

Figure 2-1 is a flow chart of the research efforts. First, efforts were made to evaluate the suitability of various joining and cutting techniques for deep-sea applications (Task 1). A pressure tank for conducting welding experiments was designed and constructed (Task 2). Some experiments were then made on arc welding under simulated deep-sea conditions (Task 3). By that time M.I.T. researchers decided that further development efforts be made primarily on two joining processes - stud welding and flux-shielded arc welding. Consequently, discussions on Tasks 4 through 7 in this report are presented on the two joining processes. Throughout this research program major efforts were made on joining processes and only minor efforts were made on cutting processes.

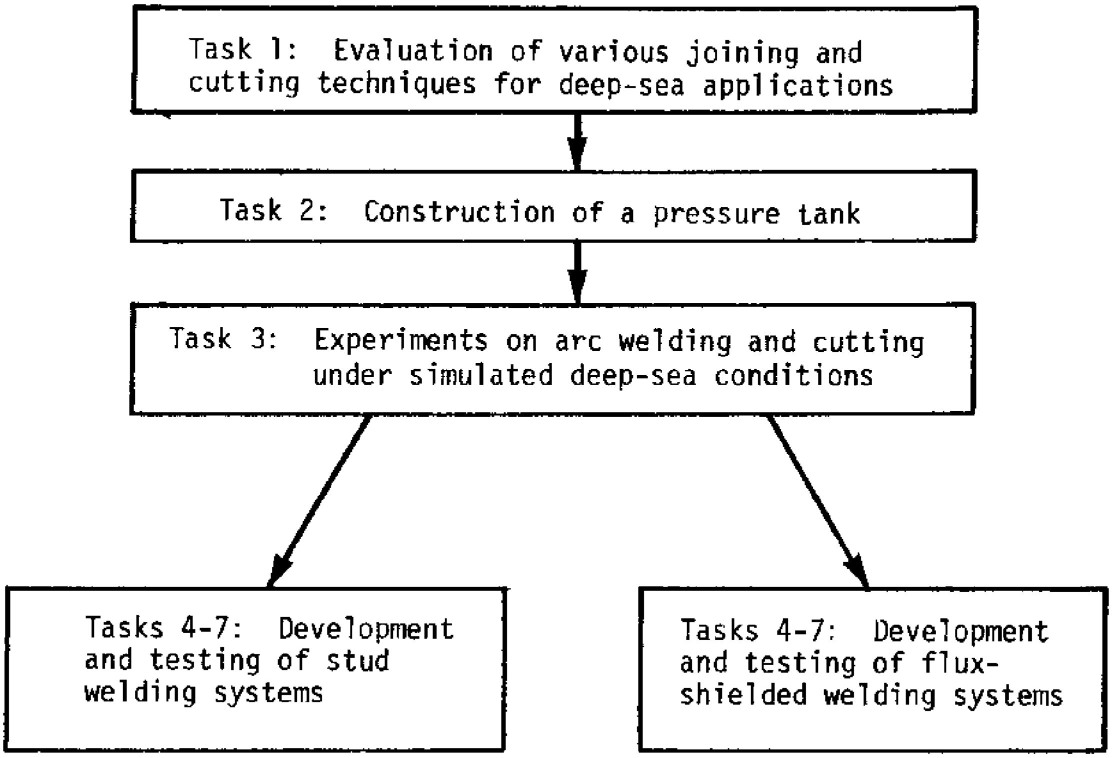


FIGURE 2-1 Tasks performed in this research program

The research was done primarily by M.I.T. students, most of whom were graduate students studying toward master's, engineer's, and doctor's degrees. In fact, most of the efforts were made as theses studies by the students under the supervision of Professor Koichi Masubuchi. Lt. Arnold P. Moore prepared a thesis entitled "Metals Joining in Deep Ocean" in June 1975. His work was an important initial effort of Task 1. During the period from July 1, 1976 through June 30, 1980 the following graduate students prepared theses on underwater welding and cutting:

Mr. Jun-ichi Chiba
Dr. Chon Liang Tsai
Mr. Subodh Prasad
Lt. David P. Erickson
Mr. Osamu Iimura
Lt. Toshioki Kataoka
Mr. Joseph Lombardi.

Titles of theses prepared by these students are listed in Section B of REFERENCES as [T12] through [T18].

Two undergraduate students, Mr. Peter C. Schechter and Mr. Roy Y. Nakagawa also worked on this research program.

Several M.I.T. staff members also provided valuable contributions. They include Mr. Anthony J. Zona, Technical instructor, and Dr. Hironori Ozaki who was a visiting research associate through December 1977 from Kawasaki Heavy Industries, Kobe, Japan.

CHAPTER 3

EVALUATION OF VARIOUS JOINING AND CUTTING TECHNIQUES FOR DEEP-SEA APPLICATIONS (TASK 1)

3.1 Introductory Remarks

The objective of Task 1 was to evaluate potential uses of various joining and cutting techniques for deep-sea applications. Factors which were considered in the evaluation include (1) the need for metals joining in the deep sea, (2) the dependency of potential processes on diving system capability and cost, as well as (3) technical problems inherent to various joining processes when they are used in deep sea.

The primary reason of conducting Task 1 was to evaluate various joining and cutting processes before launching major development efforts on selected processes in later stages of the research program. Task 1 was not intended to be an in-depth study of all joining and cutting processes which may be used for deep-sea construction and repair, nor was it intended to be a complete survey of literature. Since it was certain that our major development efforts in later stages would be on welding processes, the emphasis of Task 1 was placed on welding processes. Only limited efforts were made to survey cutting processes.

Moore [T7] studied needs, diving systems and pressure related technical problems of deep ocean metals joining technology. Chapter 4 "Depth-Related Technical Problems" of Moore's thesis is included in this report as APPENDIX B. Task 1 efforts were continued and expanded by other students and their findings were presented in their theses. For example, Iimura [T16] studied various welding and cutting processes as well as concrete fabrication. Kataoka [T17] studied underwater stud welding for deep-sea applications.

Figure 3-1 illustrates the interaction of factors important in the development of a new joining process for the deep ocean [T7]. First, a need must exist which can be met fully or partially by the employment of some metals joining process. Next, the process most suitable for meeting the requirement must be identified and technical problems associated with working at the intended depth must be solved. At the same time, a diving system must be selected which is capable of delivering and employing the joining process. In a complete underwater repair or fabrication system, additional elements may also be selected and worked into the design. After the individual elements have been integrated into a workable overall system, economic feasibility must be demonstrated. The feedback loop from operational system to need indicates that the development of a workable system which non-previously existed often leads to the identification of other similar needs.

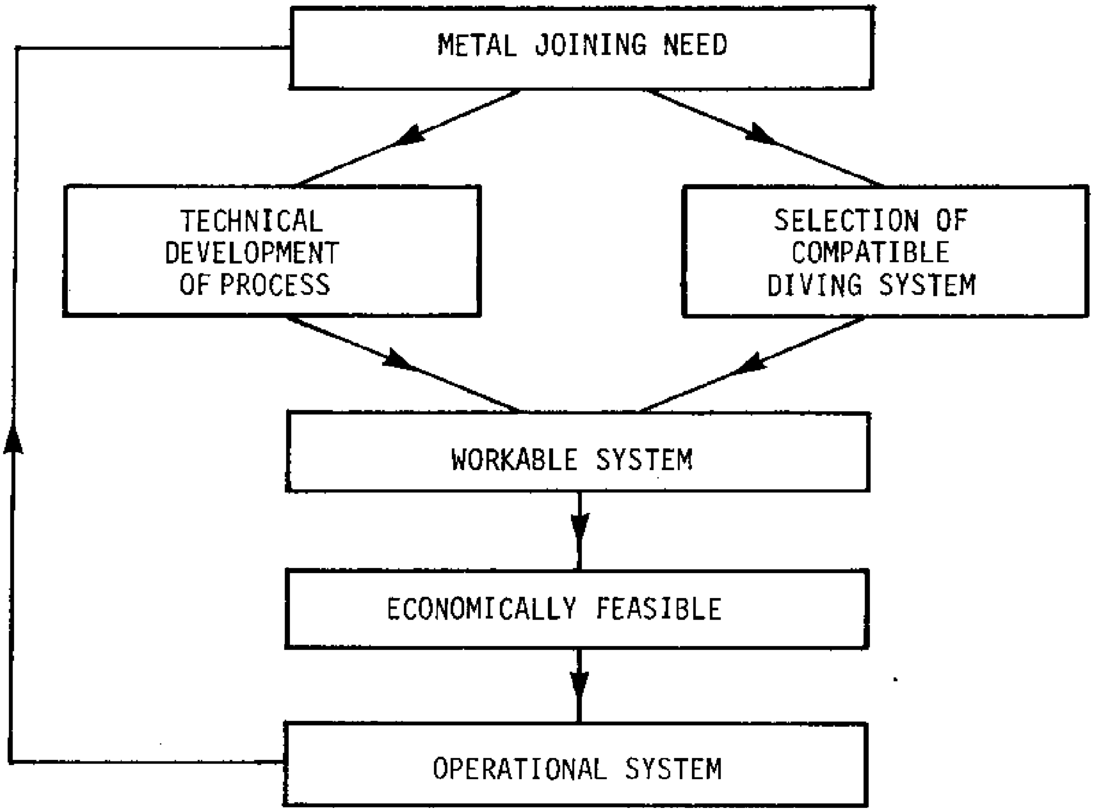


FIGURE 3-1 Development of a deep ocean joining system

3.2 Needs for Joining in Deep-Sea

The primary economic impetus to extend the metals joining technology deeper into the ocean is coming from the offshore petroleum industry [T7, P10]. During the last 20 years offshore oil drilling and other ocean related industries have grown tremendously and they are expected to grow further in the future, as discussed in 1.2 (see Figure 1-2). There is a clear trend for obtaining oil from deeper waters.

Although most of the actual offshore oil production today comes from waters less than 400 feet deep, exploratory drilling has been conducted in water depths greater than 3,000 feet as shown in Figure 1-4 [T16]. Fixed production platforms, already in use in waters of 400 feet, are being planned for waters up to 1,000 feet [T7]. Subsea production systems are presently being developed to produce in waters of 2,000 to 3,000 feet and underwater pipelines have been conducted at 430 feet and are being planned for much deeper waters.

There is a strong need for inspecting and repairing these offshore structures on site. Most of these structures are huge and can not be moved to drydocks for inspection and repair. As the number of offshore structures increases, the need for inspecting and repairing these structures increases.

There is also a need for underwater construction of new structures. At present offshore structures are fabricated on land, towed to the site and installed there. Some construction works need to be performed on site underwater. For example, some very large structures need to be joined underwater. Today pipelines are welded on a barge and they are laid underwater. However, barge laying techniques may not be feasible for the construction of large diameter pipelines in very deep water, and underwater fabrication methods are needed. Although this research program covers primarily underwater joining of metals, underwater construction of concrete also is an important subject in underwater construction in deep-sea. A survey on this subject was conducted by Iimura in his thesis study [T16].

Another unique need for deep-sea joining is related to salvaging. There is always a need for developing tools which can be used for salvaging objects, such as ships and submarines, sunken in deep-sea. These tools may be used by divers but they may also be used by deep submersibles.

There may be various other needs for developing techniques for joining in deep-sea.

3.3 Various Underwater Welding Process and Their Potential Uses in Deep-Sea

Although recent studies cover various joining processes, arc welding processes are most widely used for underwater applications. They include shielded metal arc (SMA), gas metal arc (GMA), and gas tungsten arc (GTA) processes. Underwater welding processes which are currently in use may be classified into five groups as shown in Table 3-1 depending upon the environment in which welding takes place. Dry chambers processes are capable of producing high quality welds, but they are very expensive especially when they are used in deep waters. Wet welding processes, especially wet manual SMA process are simple, less expensive and versatile; however,weld quality is rather poor and their applications are limited to repairs.

Investigators have studied underwater uses of various joining processes other than arc welding processes. Processes which have been studied for underwater applications include friction welding, stud welding, thermit welding, etc.

Some of the welding processes shown in Table 3-1 have already been used in deep-sea, although there is no clear definition of the depth which separates deep-sea from shallow-sea. Wet manual SMA welding done by a diver/welder is a simple, versatile process which can be performed under any conditions as long as the diver/welder can perform welding operations successfully. A major limitation of using the wet manual SMA process comes from diving systems, as will be discussed in 3.4. When a conventional diving system is used, it would be difficult to successfully perform welding operations beyond 200 feet deep. By use of a saturation diving system, it is possible to perform wet SMA welding in deep-sea, perhaps up to 1,000 feet or even more. In a simulated test condition oxygen cutting and wet welding have been conducted at depths up to 1,100 feet and welds have been made at depths in excess of 1,200 feet[C7].

TABLE 3-1 Classification of underwater welding processes currently in use [P8, C4, C7]

A. Dry Chamber Processes. Welding takes place in an dry environment.

1. One-Atmospheric Welding. Welding is performed in a pressure vessel in which the pressure is reduced to approximately one atmosphere independent of depth.
2. Hyperbaric Dry Habitat Welding. Welding is performed at ambient pressure in a large chamber from which water has been displaced. The welder/diver does not work in diving equipment.
3. Hyperbaric Dry Mini-Habitat Welding. Welding is performed in a simple open-bottom dry chamber which accomodates the head and shoulders of the welder/diver in full diving equipment.

B. Portable Dry Spot Process. Only a small area is evacuated and welding takes place in the dry spot.

C. Wet Process. Welding is performed in water with no special device creating a dry spot for welding. In manual wet welding the welder/diver is normally in water.

Dry chamber processes can be used in deep-sea. For example, the one-atmosphere welding can be performed at any depth as long as a necessary diving system is developed. Hyperbaric dry chamber processes also can be used in deep-sea. Weld quality is believed to be reasonably good, because welds are made in dry environment. However, the cost becomes extremely high due largely to the high cost of using dry chambers in deep-sea. Dry chamber processes have been successfully used for various jobs including repairs of underwater pipelines and offshore structures; however, much of the information on actual jobs is kept as a commercial secret. Presented here are two published examples of applications of dry chamber arc welding processes in deep waters:

(1) A paper published in the Welding Journal states that Taylor Diving and Salvage Company conducted dry habitat welding in the open sea at a depth in excess of 1,000 feet [C7].

(2) During February 1978, 40 miles north of Stavanger, Norway, teams of welders and submersible pilots successfully completed a three year, deep-water welding study [C8]. The best, part of project Weld-ap, was conducted in 300-m (1,000 feet) water depths to demonstrate the feasibility of welding at great depths under atmospheric pressure. It was initiated to solve the problems caused by welder and arc being subjected to high pressures. As a solution a system composed of a welding chamber, a support module, and a personnel transfer module has been developed.

Joining techniques which may prove useful in establishing attachment points during salvage operations include the velocity power tool, explosive welding, exothermic welding, brazing, and stud welding. Only the velocity power tool has completed development and is fully operational.

There are basically two factors which limit the use of a certain joining process for deep-sea applications as follows:

(1) Diving system limitations and costs

(2) Depth related technical problems

These subjects are discussed in the following portions of this report.

3.4 Diving System Limitations [T7,P10]

Underwater joining techniques are highly dependent on the diving systems with which they are used. Even in shallow water, poor visibility, a lack of stability and extreme cold may hamper welder performance. As welding depths increase, even stricter constraints are imposed. Unless expensive saturation techniques are employed, allowable diver working time decreases drastically as depth increases. Even saturation diving techniques are not practical beyond certain depths and submersibles or remotely controlled work vehicles must be used.

Unfortunately, the arc welding processes now being employed in shallow water require a high degree of manipulative ability which can only be afforded by a skilled welder in direct contact with the workpiece. In order to achieve this contact, the welder must be subjected to ambient pressure or the work must be enclosed in an isobaric chamber. Since the second alternative is practical only in certain cases, present construction and repair techniques, with the exception of mechanical joining devices, are essentially limited to depths that the human body can withstand. At the present time, practical diving limits are equivalent to about 1,000 feet of water, but they may be extended to 2,000 feet or possibly even deeper [C9,C10].

A study was made of several diving systems as they impact on the joining of metals underwater. Diving systems of interest can be divided into two groups as follows:

(a) Systems with direct man-work interface

1. Conventional diving
2. Saturation diving
3. Ambient pressure chambers
4. Constant pressure chambers

(b) Systems with remote man-work interface

5. Manned submersibles

6. Remotely operated work vehicles

The first group is composed of those systems which have a direct man-work interface, that is those in which the diver/operator can get hands on the work. In the second group are those systems in which extra links have been added in the form of manipulators, TV cameras or other similar devices. These systems have a remote man-work interface. Table 3-2 gives a summary of diving system limitations. Details of the study are presented in Moore's thesis [T7]. Brief explanations of these diving systems are given below.

A conventional diving system is one in which a man is exposed to ambient water pressure, but not for a period long enough that his body tissue might become saturated with inert gas. Short mission capability and generally shallow depths characterize conventional diving, with decompression required after only a few minutes of work below 100 feet. When air is used, a safe depth limit is just under 200 feet, with a helium-oxygen mixture it is less than 400 feet. At these limits, working time is extremely short if massive decompression times are to be avoided. Surface support is minimal, consisting of a breathing gas supply, a line tender, a backup diver and a decompression chamber [C11].

The tissues of a man who has been exposed to an inert gas under pressure for 24 hours have taken up practically all the inert gas they can hold at that pressure. The man is then said to be saturated at that pressure and his decompression time is unaffected by further bottom time at that depth. A total saturation diving system permits the diver to live and work at pressure continuously for the entire time the job may take, requiring only decompression when the diver leaves the system. In this manner, a much larger percentage of the time under pressure is spent working and a much smaller percentage is spent undergoing decompression [C11,C12]. Using saturation techniques divers can be kept in a living

TABLE 3-2

Summary of Diving System Limitations

Diving System	Manipulative Ability	Depth Capability	Flexibility	Support Capacity	Risk to Life
Conventional Diving	3	1	5	3	6
Saturation Diving	4	3	6	4	5
Ambient Pressure Chambers	5	2	2	5	4
Constant Pressure Chambers	6	4	1	6	2
Manned Submersibles	2	5	4	1	3
Remotely Operated Vehicles	1	6	3	2	1

6 greatest
1 least

chamber at several hundred feet and deployed to a work site for periods up to several hours (for example, up to 3 hours at 660 feet).

Several commercial diving companies, engaged in the support of offshore oil production, use underwater welding chambers to provide a dry environment at an ambient pressure for the repair of damaged sections of undersea pipelines. The forward and aft bulkheads of the chambers, perpendicular to the pipeline direction, are designed with large grooved penetrations and the bell is lowered so as to fit these directly over the pipe. Below the pipeline, once it is straddled by the bell, the grooves are closed with watertight doors. Next, water is displaced from the chamber by pressurized gas and divers enter from the bottom and fold down gratings for a work platform [C11]. A helium-oxygen mixture with an oxygen partial pressure of 6-8 psi has been found suitable. The welders breathe through a mask using a separate system of gases more suitable for sustaining life. Because the chamber is extremely humid, hydrogen cannot be removed from the chamber atmosphere and shielding gases must be used with the welding arc shelf [C13]. Since welders are at ambient pressure in these chambers, safe diving limits must be observed (for example, 540 feet in the Gulf of Mexico) [T7].

Subsea chambers maintained at a constant internal pressure of one atmosphere are one solution to the problem of working on underwater producing systems in deep water. Designed to mate with personnel transfer capsules, these chambers can be used by work crews to complete welds and perform on-site maintenance. Since personnel are not exposed to pressure or other diving hazards, workmen with no diving skill can be employed. Surface repair techniques and welding processes can be employed with little problem. The one atmosphere chamber is the only diving system with a direct man-work interface which is not severely limited in depth capability. Its primary disadvantage is that it is extremely limited in application. Work can only be performed in very small areas enclosed by a specially designed work chamber which can only be mated with a custom designed transfer capsule. The system is also expensive.

The word submersible, as it is used today, connotes no precisely defined vehicle. For the purpose of this study, a manned submersible is considered any undersea vehicle capable of transporting a man or men at a constant pressure and capable of performing some degree of manipulative work underwater. Submersibles of a variety of designs and capabilities have been built and are used for various purposes [P1]. Submersibles can be designed for use at various depths. Submersibles with manipulative ability are being built for use on the abyssal plain at depths of 15,000 to 20,000 feet [C11]. Limits, as they affect joining techniques, are not depth-related but rather determined by the manipulative devices incorporated into submersibles.

Remotely operated work vehicles may be used effectively underwater in a number of situations. Manipulators can be operated from the surface as well as from within a submersible and television cameras and sonar systems can go a long way toward replacing man's eyes underwater. Several remotely operated maintenance systems which are intended to perform predesigned functions on underwater structures are being designed. These include Shell's Seafloor Pipeline Repair System(SPRS) and Exxon's Submerged Production System(SPS) maintenance unit [C14,C15]. The use of remotely controlled vessels to recover weaponry underwater is now well advanced [C16]. Remotely operated work vehicles may not be as flexible in usual situations as manned submersibles, but they should prove useful in a number of tasks.

In comparing these diving systems Moore [T7] studied manipulative ability, flexibility, support capability, risk to life as well as depth capability. Only a brief discussion on support systems is presented here.

Many underwater joining processes require a source of electrical power and some of these processes require shielding gas as well. In relatively shallow waters, these items can be provided by cables and hoses from the surface. As depth increases, however, these simple solutions may no longer be feasible. Figure 3-2 shows voltage drop in power supply cables [C5]. Power losses in cables can become significant when very long cables are used for welding in deep-sea. Power requirements for joining processes are therefore much less restrictive if submersibles and remotely operated work vehicles are used. It is also more practical to carry shielding gas in cylinders on submersibles and work vehicles due to the pumping head required at extreme depths for a hose system.

3.5 Cost-Depth Relationships

The major operational cost components of any total underwater joining system are the expenses associated with diving. Costs incurred by the operation of the joining process itself are normally quite small. This is particularly true for deep water systems since diving costs increase rapidly while process costs increase only slightly, if at all.

In many cases, selection of a diving system must be based on performance consideration alone. Depth constraints and manipulative limitations act to narrow the choice of diving systems considerably. However, cost considerations will enter into the choice in a great many cases so that a knowledge of cost-depth relationship is essential. Because of the importance of the subject an analysis was made of the cost of diving systems. We experienced, however, considerable difficulty in obtaining data, since most of the cost data are kept within the organization as secret. It should be emphasized that data presented here show only general trends

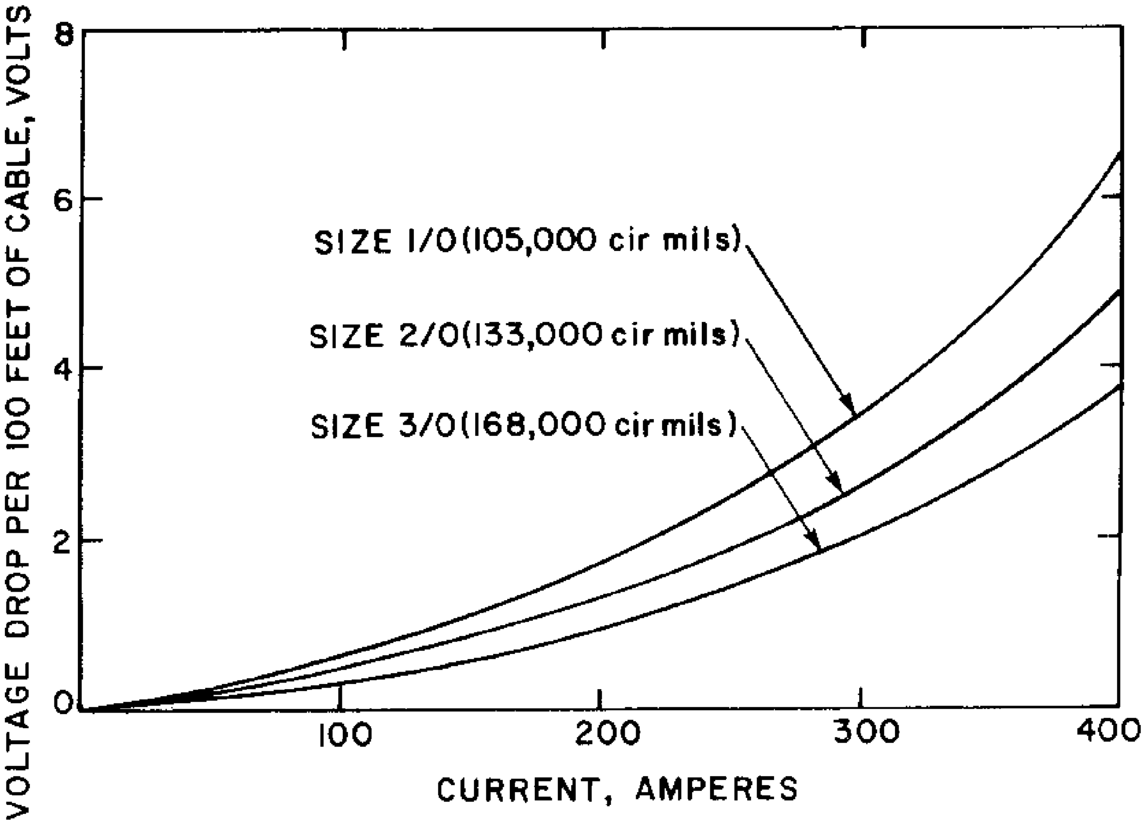


FIGURE 3-2 Voltage drop in power supply cables [C5]

and that specific trade-offs should be based on precise data for individual systems. It should also be noted that the cost analysis was made during the 1974/75 academic year.

Figure 3-3 presents cost relationships for depths of up to 1,000 feet and Figure 3-4 presents similar information for depths of up to 20,000 feet. Hyperbaric chamber costs, which are not shown, are somewhat higher than those of saturation systems operating at the same depths. One atmosphere chamber costs were undetermined in this survey but should approximate those of manned submersibles. One major factor which affects the relative position of the curve is the cost of surface support equipment. This figure is highly variable, depending upon the particular support vessel chosen. In interpreting these figures it must be remembered that no attempt has been made to adjust the curves to account for the relative efficiencies of the systems under consideration. As a result, both cost per work hour and hours required to complete the job must be considered in determining the most economical diving system for a particular job. Supporting data and calculations are presented in the appendix of Moore's thesis [T7].

In Figure 3-3 it can be seen that conventional surface diving techniques have no real competition in shallow water, at least for tasks of short duration. This is due to the fact that support and capital cost for conventional systems are small. However, as depth or bottom time increases, larger decompression debts are incurred and the conventional diver must spend a greater portion of his time under pressure in decompression and a small portion in working[C11]. Conventional diver efficiency also decreases with depth. Depth does not, however, make as much difference in the efficiency or work cycle of a saturated diver. He needs to orient himself to depth and the job at hand only once so his overall efficiency is higher. The number of work hours per day in a saturation system is largely unaffected by depth. At 300 feet, the saturated diver can spend approximately three times as long working hours, per unit time under pressure, as can the conventional diver and his efficiency will be 25-50

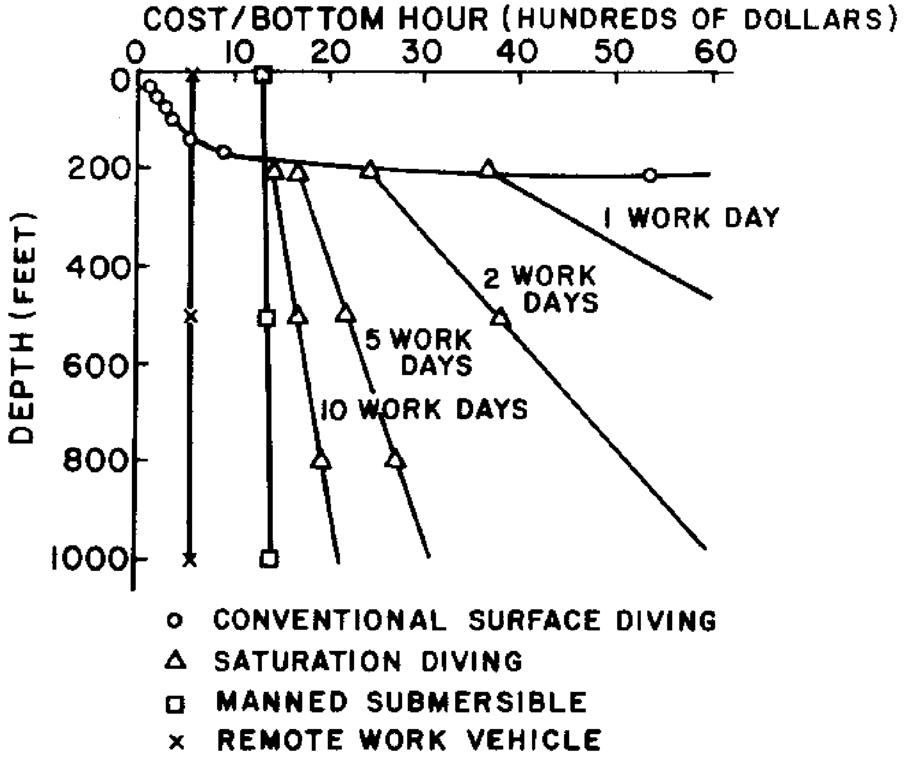


FIGURE 3-3 Cost vs. depth for diving systems (0-1000 feet)

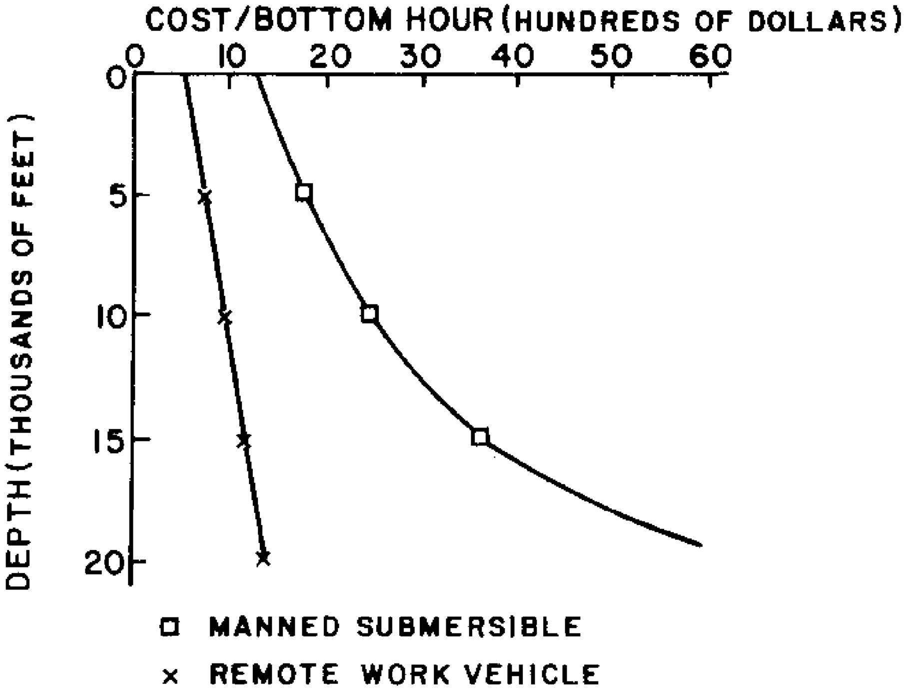


FIGURE 3-4 Cost vs. depth for diving systems (0-20,000 feet)

percent more at this depth. The increase in working time and efficiency makes up for increased support costs for jobs of longer duration [C12].

Due to a marked difference in capacity, manned submersibles and remote work vehicles are rarely in competition with conventional and saturation diving systems [C17]. As both Figures 3-3 and 3-4 illustrate, cost increases with depth are much less for these systems. Several "standard" submersibles for relatively shallow depths can be purchased, but remote systems and many submersibles are one-of-a-kind models and are still more expensive than they would be if they were more widely produced. This accounts for the relative closeness of the two curves. As remote work vehicles become more standardized their cost in comparison with submersibles should drop [C11,C18].

Manned submersibles are most economical for missions lasting a few hours because performance and time on bottom are limited by on-board power. Remote vehicles are particularly valuable for long missions in very deep water in the performance of tasks inherently dangerous to divers and submarines. No price tag can be put on human life [C16,C18,C19].

3.6 Depth Related Technical Problems

As operating depths increase, the effects of pressure on joining processes become of greater importance. Pressure effects on the arc are common to all electric arc welding processes and are examined first. Other processes also have problems induced by increased operating depths but these are more varied and must be treated individually. APPENDIX B presents detailed discussions on depth-related technical problems of current joining processes.

A welding arc is a sustained electrical discharge through a high temperature, high conductivity column of plasma and is produced by a relatively large current, in the neighborhood of 200 amperes, and a low voltage of from 35 to 50 volts. All welding arcs are constricted to some extent by electromagnetic forces, but an underwater arc is also compressed by hydrostatic forces and cooling effects. Cooling is caused by the surrounding water as well as by hydrogen dissociated from the steam in the welding bubble. Constricting forces combine to increase the rate of collision among electrons, ions and neutral particles causing a high pressure region. In order to maintain the rate of current transfer, core temperatures must increase. Core temperatures in underwater arcs can range from 5,000 to 50,000°K depending on the degree of ionization and arc constriction [C20].

The very high arc core temperatures found at greater depths greatly increase arc penetration. This can have both beneficial and detrimental effects. Increased penetration, accompanied by more rapid metal transfer, can lead to higher, more efficient deposition rates. On the other hand, at high pressures such as those found on the deep ocean floor, increased penetration can lead to burnthrough [C20]. In GMA welds made under pressure in a dry atmosphere, it was found that the filler metal feeding speed could be adjusted to offset these effects. Arc voltage and welding travel speed were less influential in controlling weld penetration and shape [C21].

As depth and hydrostatic compressive forces increase, the current density of the arc increases and a higher voltage is required to maintain a constant arc length [C22]. Several researchers have detected an apparent increase in SMA current requirements with depth [P7,C20] but this trend has not been confirmed during commercial work at sea. In this work it has been found that it is necessary to increase current for underwater welds approximately 10 percent over that required for air welds and to increase current as cable length is increased, but no direct correlation between depth and current demand has been noted [T7].

Increasing the pressure on an electric arc is detrimental to arc stability and results in a tendency for metal transfer to revert from the more efficient spray mode to the less desirable globular mode. At low pressures, near atmospheric, arc stability is relatively insensative to voltage, but at high pressures, increasing voltage increases stability and delays the onset of globular transfer. However, this voltage increase does not completely eliminate instability and some loss of arc efficiency occurs [P7,C10,C21,C22].

Welds made underwater are protected somewhat from the severe quenching action of the surrounding water by an envelope of gas dissociated from the water by the heat of the welding arc [P7]. This protection diminishes somewhat with depth since hydrostatic pressure compresses the gas bubble and reduces its size. Increased pressure also affects the behavior of gases supplied to shield the weld. The density of the gas is increased and higher flow rates are required. In some cases, flow rates as high as ten times those used on the surface have been needed [C23].

Liquification of shielding gases places a depth limit on their use. Of the gases suitable for shielding, argon and hydrogen remain gaseous at the greatest pressures. At 273°K, argon liquifies at 3570 meters and nitrogen at 5090 meters. Heating of a gas may extend its range slightly, but practical considerations limit this action [C20].

Weld metal porosity is reduced in welds made under pressure. This effect is believed to be due to supression of bubble formation, not to a decrease in the amount of gas in the weld [C22]. If this is the case, chemical problems will remain unchanged. Wet electrode coatings can cause excessive porosity in SMA welds, but improved electrode coatings and methods of storing electrodes in a dry environment prior to use have helped to overcome this problem.

Pressure increases the rate at which carbon, manganese and silicon deoxidants combine with oxygen and leads to their removal from the weld metal [C24].

Since the bubble atmosphere surrounding an underwater arc is caused by the dissociation of water, it may be up to 93 percent hydrogen. Hydrogen from the weld bubble dissolves into the weld puddle and causes porosity, embrittlement and cracking [C23]. The severe quenching effect of the underwater environment enhances the formation of brittle martensite and increases embrittlement and cracking problems [P7]. Hydrogen solubility in the weld metal is governed by Sievert's Law and increases as the square root of hydrogen pressure, indicating that hydrogen induced problems may become more serious at greater operating depths [C20].

The use of austenitic electrodes has resulted in the elimination of underbead cracking during underwater multipass SMA welding. An austenitic weld metal microstructure is capable of storing large quantities of hydrogen which keeps the hydrogen away from the crack sensitive HAZ, avoiding underbead cracking. In steels having a high carbon equivalent, this technique has proven reliable down to a depth of 25 meters. The development of new electrode coatings has also been instrumental in extending the operational depth of the SMA process for low carbon steels to over 60 meters [C25].

Much less research has been conducted on the effects of pressure on processes other than electric arc welding. Velocity power tools employ sealed barrels to overcome the problem of accelerating stud projectiles in a high pressure environment. Devices with sealed barrels provide adequate penetration at depths up to 300 meters [C26]. Methods of removing water form the weld mold and ensuring the flow of metal from the reaction chamber to the mold must be developed to make exothermic welding a practical deep ocean process [P4]. In shallow underwater explosive welding, secondary charges timed to explode a fraction of a second prior to the main charge are used to expel water between the joining surfaces. At greater depths, this technique may not be feasible since prohibitively large charges may be needed to overcome hydrostatic forces.

Mechanical joining techniques are versatile, adaptable to remote operation and are not affected by pressure. Their use is being planned in several deep water repair systems [C27,C28] and, in the absence of other processes, it is expected that many of these devices will be developed to meet future joining needs at depths beyond diver limits.

It appears that devices capable of meeting deep salvage needs can be developed which require little manipulative ability and are thus suitable for employment with submersibles and remote vehicles. Diving systems impose no depth limit on these devices but power requirements are a major constraint. Velocity power tools appear to be the most promising devices now in existence for use in deep ocean salvage operations. These tools are small, inexpensive, have a self-contained energy source and lend themselves easily to remote operation. They can be used to attach a variety of stud-like fittings [C26]. Exothermic processes have the same advantages but are not limited to the attachment of studs, since welds are not size or shape limited. One possible application is the attachment of repair sleeves to damaged subsea pipelines. Explosive welding is another self-contained technique which may be useful in the deep ocean. However, welds with good bonding characteristics are difficult to produce consistently, even on the surface. Arc stud welding devices are also being considered for deep ocean application but require rather large pulses of electrical power which can, at present, only be provided by cables from the surface [T7,T8].

3.7 Conclusions of Task 1 and Recommendations for Later Tasks

1. Wet manual shielded metal arc process using a welder/diver in a conventional diving system is a simple, economical, and versatile method primarily for making repair welds. However, its use is restricted to a depth less than about 200 feet due primarily to diving limitations.

2. By use of a saturation diving system the work capability of a diver can be extended to deep waters in excess of 1,000 feet. Wet SMA process may be used in deep sea for making repairs and other non-critical welds. One important research topic is to develop simple-to-operate joining systems which can be operated by divers. To obtain high-quality welds the systems should use dry spot techniques so that welding is performed in dry environments. The systems may be operated from a submersible by using

a remotely controlled manipulator.

3. Dry chamber processes can be successfully used for deep-sea applications. For example, the one atmospheric welding can be performed at any depth as long as a necessary diving system is developed. Mechanisms of one atmospheric welding are essentially the same as those in ordinary air welding. Hyperbaric dry chamber processes also can be used in deep-sea. These processes have been successfully used for various jobs including repairs of underwater pipelines and offshore structures. Weld quality is believed to be reasonably good, because welds are made in dry environment. Besides high pressure, experienced in hyperbaric processes in deep-sea, an important technical problem is to maintain very low humidity environment comparable to that required for high-quality welding jobs on land. It is well known, even in welding on land, that hydrogen causes major problems in welding high-strength studs and aluminum alloys. Hydrogen is a major cause of cracking in welding high-strength studs, while hydrogen is a major cause of porosity in welding aluminum alloys. The major disadvantage of dry chamber processes is the extremely high cost due primarily for using dry chambers in deep-sea.

4. Recommendations for Later Tasks. On the basis of the findings obtained in Task 1 it was recommended that major efforts in later tasks be placed on the development of simple-to-operate joining systems which can be operated by divers.

CHAPTER 4

CONSTRUCTION OF A PRESSURE TANK (TASK 2)

In order to conduct a systematic experimental study of underwater welding in deep water it is essential to have a facility capable of making welds in a controlled environment. To do this a pressure vessel along with necessary auxiliary equipment for pressurizing and depressurizing is needed. Also needed are means for producing welds in the tank using different techniques along with various devices recording welding conditions and observing welding phenomena in process.

The objective of Task 2 was to construct a pressure tank for welding experiments. First a survey was made of previous published information on experiments at simulated depths, and an assessment was made of the requirements and budgetary limits. Efforts were then made to design a pressure tank, construct it, and then test the tank after it was constructed. The efforts were made through a cooperative work by a group of people including Ozaki, Prasad, Tsai, and Zona. Details of the efforts are presented in the thesis by Prasad [T14].

The cost required for the construction of the tank and the purchase of the auxiliary equipment and the welding setup was covered by matching funds from a group of companies including:

Hitachi Shipbuilding and Engineering Co.

Ishikawajima-Harima Heavy Industries

Kawasaki Heavy Industries

Mitsui Engineering and Shipbuilding Co.

Nippon Kokan Kaisha

Sumitomo Heavy Machinery Co.

4.1 Important Design Decisions

In early stages of the design of the facility a series of important decisions were made which determined basic features of the M.I.T. Facility. Some of the important features are described below.

1. Depth Capability. The first important design consideration that was decided was the depth capability of the facility. As the depth capability increases the cost of the facility increases. Since most of the offshore activities are taken at depths up to 1,000 feet, this figure was used as an initial target depth. We also wanted to build the pressure tank at a cost less than $10,000. The final decision was to have the depth capability of 700 feet at a pressure of 300 psig.

2. Underwater Welding. The second important design consideration was how to create the environment for underwater wet welding. There were basically two methods as follows:

   (a) To build a pressure tank which could be completely filled with water

   (b) To build a pressure tank with a dry environment and conduct underwater welding experiments by placing specimens in a pan containing water and put the pan in the tank under pressure

   The first method would certainly simulate underwater wet welding more closely than the second method. However, this creates a difficult problem of how to place welding equipment in pressurized water. We decided to select the second method primarily because it was much easier and more economical to build the facility than selecting the first one. Another important factor for selecting the second method was that most of high-quality underwater welding jobs are presently done by dry chamber techniques and uses of wet welding techniques are generally limited to repair jobs, as discussed in Chapter 3. The second method simulates hyperbaric dry chamber process.

3. Welding Experiments. The facility should be able to handle various welding processes. It was decided that all welding experiments should be made completely automatically by use of a remote control device placed outside the pressure tank. The welding system should be designed in such a way that welding experiments can be performed by personnel having no welding skill.

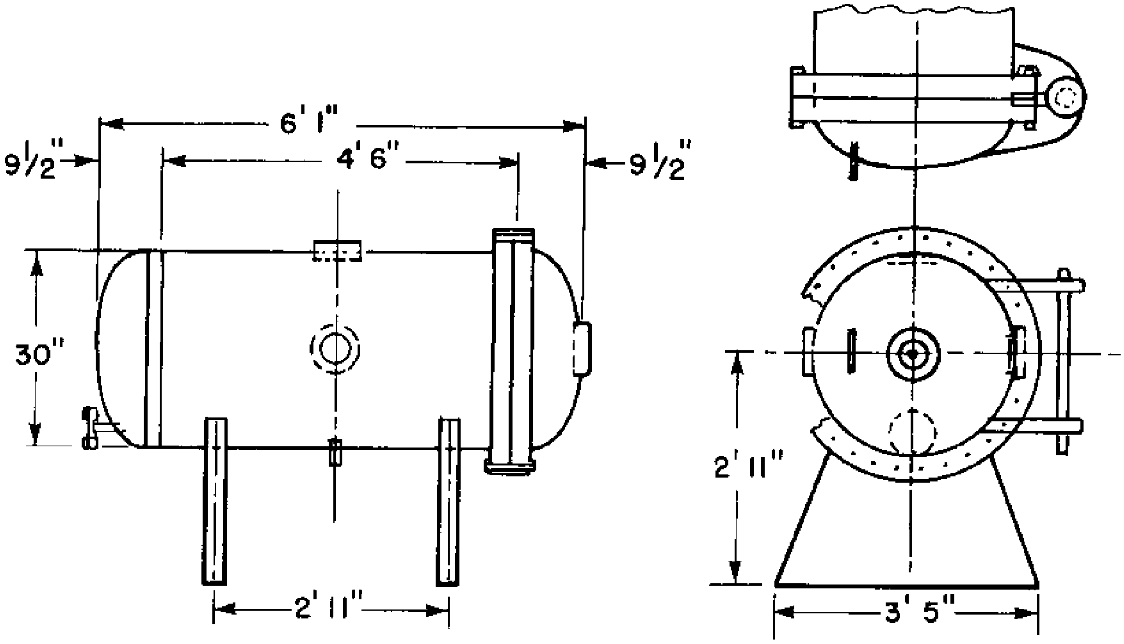
4.2 Construction and Testing of the Facility

Prasad's thesis [T14] described details ofdesign, construction, and testing of the M.I.T. facility. Presented here are some of the important aspects.

Pressure Tank. Figure 4-1 shows some details of the pressure tank. M.I.T. researchers made initial designs, while the M.S. Charlestown Welding and Engineering Co., Charlestown, Massachusetts prepared the final detailed design and did actual construction of the tank.

The tank is 6 feet long and 30 inches in diameter and it is made of low-carbon steel. The tank has two convex ends, one of which can be fully open to give easy access to the interior. It is placed horizontally on a set of stands and the center of the cylinder is 35 inches above the ground. Figure 4-2 shows an overall view of the pressure tank while one end is open.

The tank has three viewing points so that the inside of the tank can be illuminated through one and two people can observe the welding experiment at the same time. In order to fit different types of welding equipment required for cable feed throughs inside the tank without making new holes or blanking an existing one, the tank has one porthole with a cover. The cover is used for fitting all cable and pipe glands. Thus, a different cover can be used for each type of welding equipment.



Note: See Prasad's thesis for further details [T14]

FIGURE 4-1 Design drawing of the pressure tank

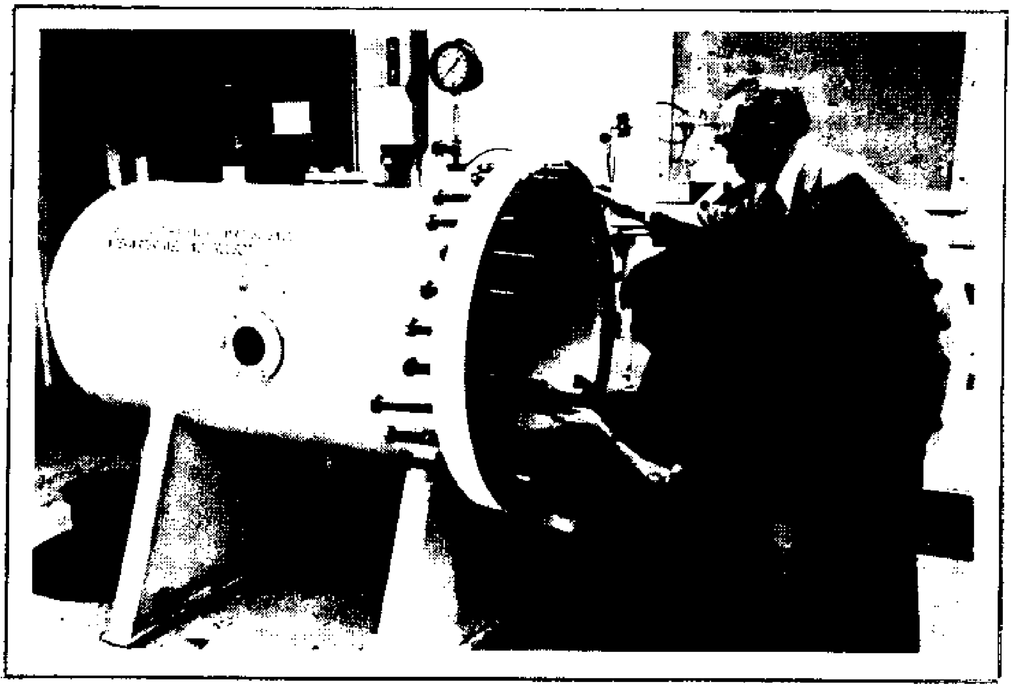


FIGURE 4-2 Overall view of pressure tank while one end is open

Pressurization System. To get the pressure equivalent to different water depth in the pressure tank a pressurization system is required. The pressure in the tank can be built by hydraulic pressure, compressed inert gas or compressed air. It was decided not to employ the hydraulic pressurization as discussed earlier. The tank can be pressurized by either inert gas or compressed air. The compressed air system has been used for most experiments because of the cost advantage over the inert gas system. An electrically driven compressor is used to produce compressed air.

Welding System. The M.I.T. facility is designed in such a way that experiments using various welding processes can be made provided that the equipment is small enough to be placed in the pressure tank. The basic welding process employed, however, is the gas metal arc process. Consequently the GMA welding system is described here.

The GMA welding system consists of three parts: the power supply, the travel system and the welding gun. The power supply is placed outside the tank, while the travel system and the welding gun are placed inside the tank as shown in Figure 4-3. The power supply used is an AIRCOMATIC Model CV-450 welding machine made by AIRCO. It is a multipurpose machine of the constant potential type with a maximum current of 450 amperes. The cable from the power source enters the pressure tank via pressure fittings.

The welding gun used is an AIRCO's MIGet welding gun model AH20-E with AIRCOMATIC Control Model AHC-M/S. It uses consumable wire electrodes 0.030 to 0.045 inch diameter. The ordinary welding gun has all its operational controls on its handle. In order to operate the welding gun from outside the pressure tank, some modifications of the gun had to be made. This consisted of providing external switch for gas flow welding (motor and power supply) and wire speed control. Electrical pressure fitting was used for connecting control cables from the gun to the controls outside the gun.

The gas most frequently used is Argon-25% CO_2. The gas from the

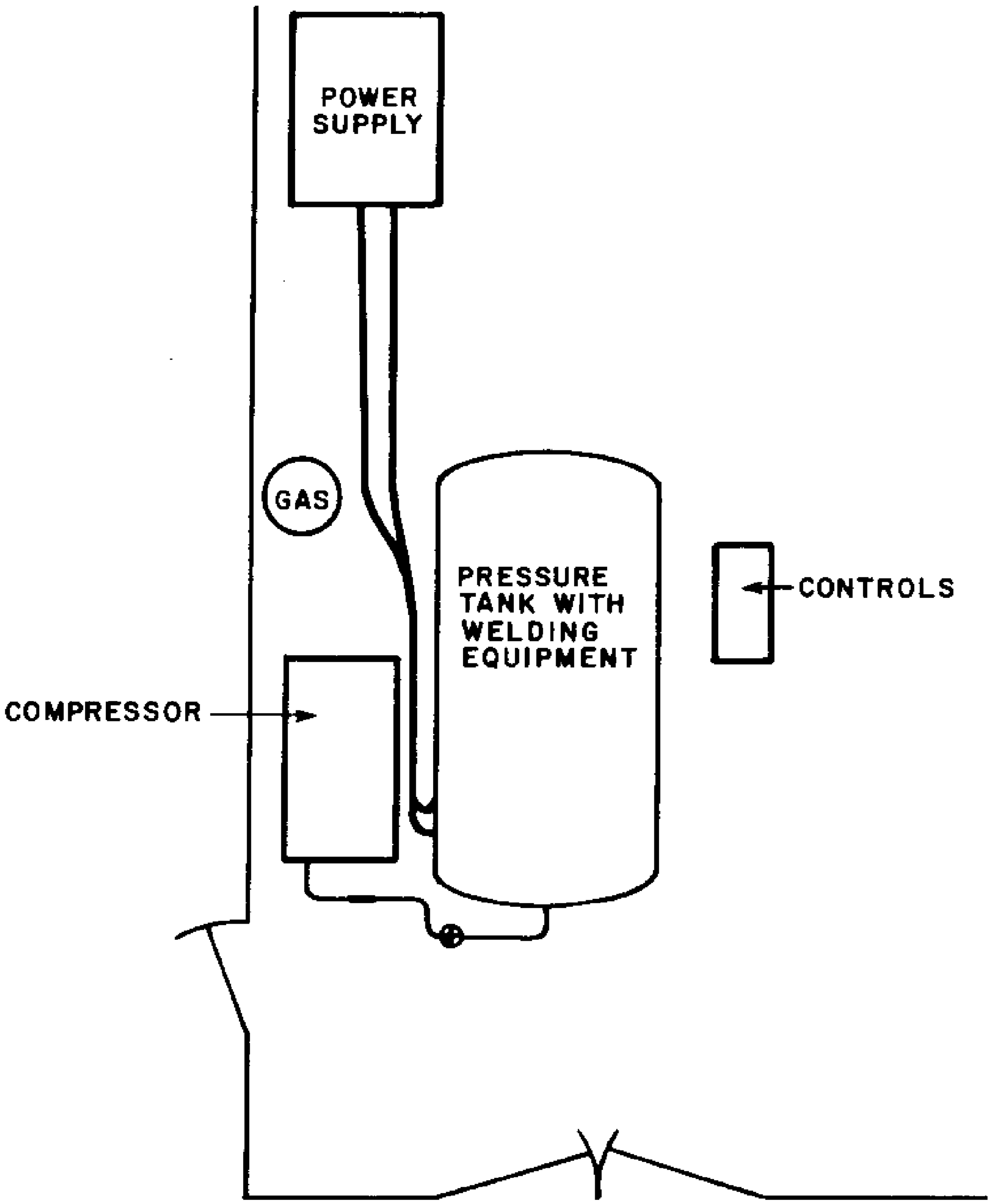


FIGURE 4-3 Floor plan showing the experimental apparatus layout

storage cylinder passes through a pressure regulator, then via pressure fitting into the tank.

The travel system used for the movement of the welding gun is Welding Tooling Corporation Bug-O (Experimental Model) system with remote control for:

a. Travel speed

b. Start, stop and direction of travel

The track for the travel system has magnetic mounts, with hinged joint, for mounting on a curved surface. The standard mounts with a single hinged assembly were found unsatisfactory due to the high curvature of the pressure tank walls, hence the same was modified and two hinged joints provided. The power and control cables to the carriage unit have pressure fittings on them where they enter the tank.

Figure 4-4 shows the welding system inside the pressure tank. It shows the welding gun mounted on the travel system.

Measuring Devices. The present setup is capable of making the following measurements during welding:

a. Arc voltage

b. Welding current

c. Travel speed of the carriage

d. Temperature changes of a specimen being welded

Arrangements can be made to make other measurements.

4.3 Operating Experience and Summary of Capabilities

The M.I.T. facility has been operating very satisfactorily. Many welded specimens have been prepared under various levels of pressure. It is worth mentioning that no qualified welder was used in preparing these welded specimens. All specimens were prepared by students (mostly graduate

FIGURE 4-4 The welding system inside the pressure tank showing the welding gun mounted on the travel system

students) with no training as welders.

As a summary operational capabilities of the M.I.T. facility are described below:

Tank size: 6 feet long, 30 inches in diameter

Maximum simulated working depth: 700 feet (300 psig)

Position: downhand (can be modified for all positions)

Maximum weld length: 2 feet

Joint types: Bead-on-plate, butt joint, lap joint, and tee joint (can be modified for other types of joint)

Welding processes: GTA, GMA, shielded metal arc, flux-shielded, stud welding (Can be modified for other processes)

Figure 4-2 shows the overall view of the tank, while Figure 4-3 shows the welding system inside the tank. In making a welded sample, the sample is placed in the tank and the door is closed. Pressure is applied by activating a compressor located outside the tank. Welding is performed completely automatically by merely pressing an appropriate button. The operator standing outside the tank can observe the welding arc through the window on the side wall of the tank.

When underwater welding is necessary, specimens to be welded are immersed in water contained in a pan. Then the entire setup, including the welding machine, specimens and pan, is placed in the tank and subjected to a certain pressure. In this way underwater welding in deep-sea conditions can be simulated without building extremely expensive equipment.

CHAPTER 5

EXPERIMENTS ON ARC WELDING AND CUTTING UNDER SIMULATED DEEP-SEA CONDITIONS (TASK 3)

5.1 Introduction

The objective of Task 3 was to study effects of water pressure on arc welding characteristics and properties of welds. Although some studies were made on this subject, most of the experiments conducted were not systematic and conclusions drawn by different investigators were often conflicting. For example, researchers at Battelle Memorial Institute reported [C30]:

> "Welds made underwater with AWS E6013 electrodes at 295, 680, and 1,200 feet simulated depths had excessive porosity, while welds made at sea level pressure (but underwater) were sound. Welding with reverse polarity appeared to reduce the size and amount of porosity although sufficient welds were not made to verify this performance. The cause of this porosity is not known although it probably is related to more rapid freezing of the weld metal at the greater depth."

On the other hand, an investigator of the Technische Hogenschool Delft stated in a letter to M.I.T. researchers as follows [C31]:

> "It was observed that in all gases mentioned the amount of porosity in the weld metal sharply increased with an increasing pressure up to 3.5 atmosphere and decreased again at still higher pressures. (But the experiments were not performed underwater.) Other observations were a decreasing weld bead penetration with increasing pressure, while the optimum arc current range became very small at the high pressures."

The work referred to above was conducted by the working group on underwater formed by the Netherlands Welding Society.

Only limited information was available on the effects of pressure on arc welding characteristics and properties of welds made underwater. When Task 3 was conceived there was a strong possibility that a company would provide a large amount of matching funds to conduct an extensive research:

(1) To determine effects of water pressure on arc welding characteristics

(2) To determine effects of water pressure on metallurgical and mechanical properties of welds

Unfortunately the plan did not materialize and the scale of Task 3 had to be reduced considerably. In addition, M.I.T. researchers experienced considerable delays in construction and testing of the deep-sea underwater welding simulation facility. Although most of the construction and testing of the pressure tank was completed by the fall of 1977, they spent considerable time in installing welding systems which required a number of modifications. M.I.T. researchers were very anxious to go on to later phases of the research program of which objectives were to develop new underwater welding systems rather than obtaining fundamental data on processes which are currently in use.

In the fall of 1977 Prasad [T14] conducted an experimental study on the effect of pressure on gas metal arc (GMA) and flux-shielded arc (FSA) welding processes in dry environment. This is the first experimental study using the new deep-sea underwater welding simulation facility. In the spring of 1978 Erickson [T15] studied the effect of pressure on FSA welding in water.

5.2 Prasad's Study on Effects of Pressure on Gas Metal-Arc Flux-Shielded Arc Welding in Dry Environment

Prasad [T14] conducted an experimental study on the effect of pressure on gas metal arc (GMA) and flux-shielded arc (FSA) processes in dry environment. Experiments were carried out by making bead-on-plate welds. The plates were of low-carbon steel to specification AISI-1020, and the sizes of the plates were 10" x 6" x 1/4" and 10" x 6" x 1/8". Experiments were carried out to find the welding parameters that gave satisfactory welds at pressures of 50, 100, 150, 200, and 280 psig, corresponding to 114, 227, 340, 455, and 635 feet, respectively of water depth. The effect of pressure on welding arc stability, weld shape factor, and the hardness of the weld metal and the heat affected zone was examined.

5.2.1 Experiments to Find Optimum Welding Parameters at Different Pressures

Bead-on-plate welding experiments were carried out to find the welding parameters that gave satisfactory welds at pressures of 50, 100, 150, 200, and 280 psig. The welding parameters that gave the most effect on weld bead shape and quality are:

a. Welding voltage

b. Welding gun-to-plate distance

c. Travel speed

The optimum values of these parameters were known for welding at atmospheric pressure. The same values were used initially when welding at a higher pressure. Of these three parameters, two were kept fixed, the third was varied, and its effect on the weld-bead shape was examined.

1. Variation of Welding Voltage. GMA welds were made at pressures of 50 psig with the welding voltage set at 23.5, 25, 30, 34 volts. Welding voltage for satisfactory welds at atmospheric pressure was 25 volts. The weld bead was both narrow and wavy for welding voltages of 23.5 and 25 volts. At voltages of 30 and 34 volts the weld bead became less wavy and flat. The amount of spatter increased with welding voltage. FSA welding required an increase in the welding voltage with increase in pressure to give satisfactory welds.

2. Variation of Welding Gun-to-Plate Distance. The distance between the gun and the work plate for laying a satisfactory bead was

5/8 inch. The reduction of this gap caused the electrode to stab in the weld puddle. An increase in the gap caused the weld bead to become narrow, wavy, and discontinuous. Tests were carried out at 50 and 100 psig, to see the effect of changing the distance. It was seen that 5/8" gave satifactory welds at both pressures.

3. Variation of Travel Speed. Travel speed had to be reduced as the pressure in the tank was increased to maintain satisfactory weld bead shape. The travel speed required for the six pressure conditions tested are given in Table 5-1, for both GMA and SMA welding processes.

TABLE 5-1 Travel speed required at different pressures for satisfactory welds [T14].

Pressure	Gas met arc welds		Flux-shielded welds	
	Setting	Speed inches/min.	Setting	Speed inches/min.
Atmospheric	2.0	13.5	2.0	13.5
50psig	1.8	12.0	1.8	12.0
100psig	1.7	11.5	1.7	11.5
150psig	1.6	11.0	1.6	11.0
200psig	1.6	11.0	1.6	11.0
280psig	1.5	10.5	1.5	10.5

5.2.2 Effects of an Increase in Pressure on the Welding Arc

The output of the high speed chart recorder giving the welding voltage and current was used to study the welding arc in terms of metal transfer, arc voltage, welding current and arc stability for the GMA and FSA processes at 0 (ambient), 50, 100, 200, and 280 psig.

Gas Metal Arc Welding. The results of experimental observation on the effect of an increase in pressure on the welding arc in the GMA process were as follows:

(a) The metal transfer mode was by short-circuiting in the arc at all pressures.

(b) The number of short-circuits per second decreased as pressure increased.

(c) The welding arc voltage remained almost unchanged as pressure increased.

(d) The welding current remained almost unchanged as pressure increased.

The actual experimental observations are given in Table 5-2. Figure 5-1 is a sample of the output from the chart recorder at 200 psig, giving welding current and arc voltage.

Flux-Shielded Arc Welding. The result of experimental observations on the effect of pressure on the FSA welding process may be stated as follows:

(a) As the arc voltage and welding current remained steady, the metal transfer was not by the short-circuiting mode

(b) The welding voltage increased with increasing pressure

(c) The welding current increased with increasing pressure.

The results of experimental observations are given in Table 5-3. Figure 5-2 is a typical representation of the welding current and arc voltage changes during welding at 200 psig. Fluctuations of welding current and arc voltage during the FSA welding were considerably less than those in the GMA welding, as shown in Figures 5-1 and 5-2. This shows that flux-shielded arcs are more stable than gas metal arcs.

TABLE 5-2 Effect of pressure on the arc characteristics for GMA welds [T14].

Pressure	Arc voltage (volts)	Welding current (amperes)	Arc Stability	
			Arc Type	Frequency (seconds)
Atmospheric	25	100	Short-circuiting	37
50psig	25	95	-do-	24
100psig	26	95	-do-	14
150psig	25.5	100	-do-	12
200psig	25.5	100	-do-	12
280psig	25	100	-do-	12

TABLE 5-3 Effect of pressure on the arc characteristics for flux-shielded arc welds [T14].

Pressure	Arc voltage (volts)	Welding current (amperes)	Arc Stability	
			Arc Type	Frequency (seconds)
Atmospheric	25	150	Continuous	-
50psig	26	150	-do-	-
100psig	26	160	-do-	-
150psig	27	165	-do-	-
200psig	28	175	-do-	-
280psig	28	175	-do-	-

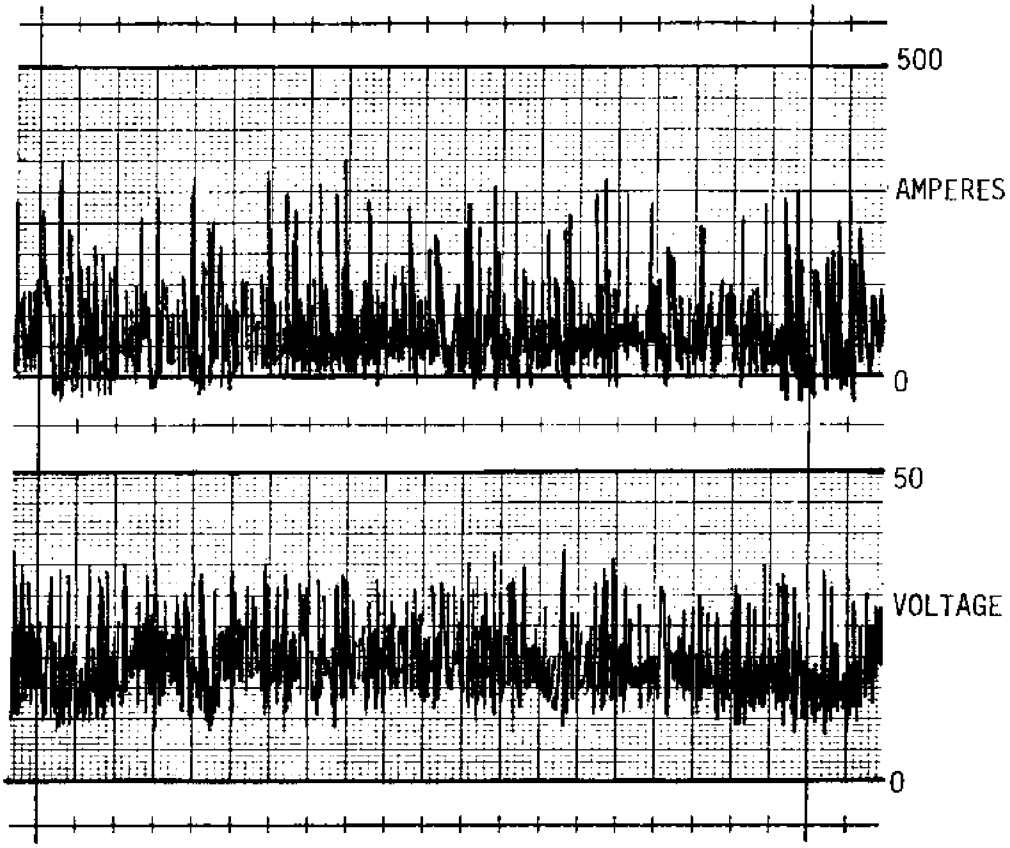


FIGURE 5-1 Voltage-current trace for GMA process at 200 psig [T14]

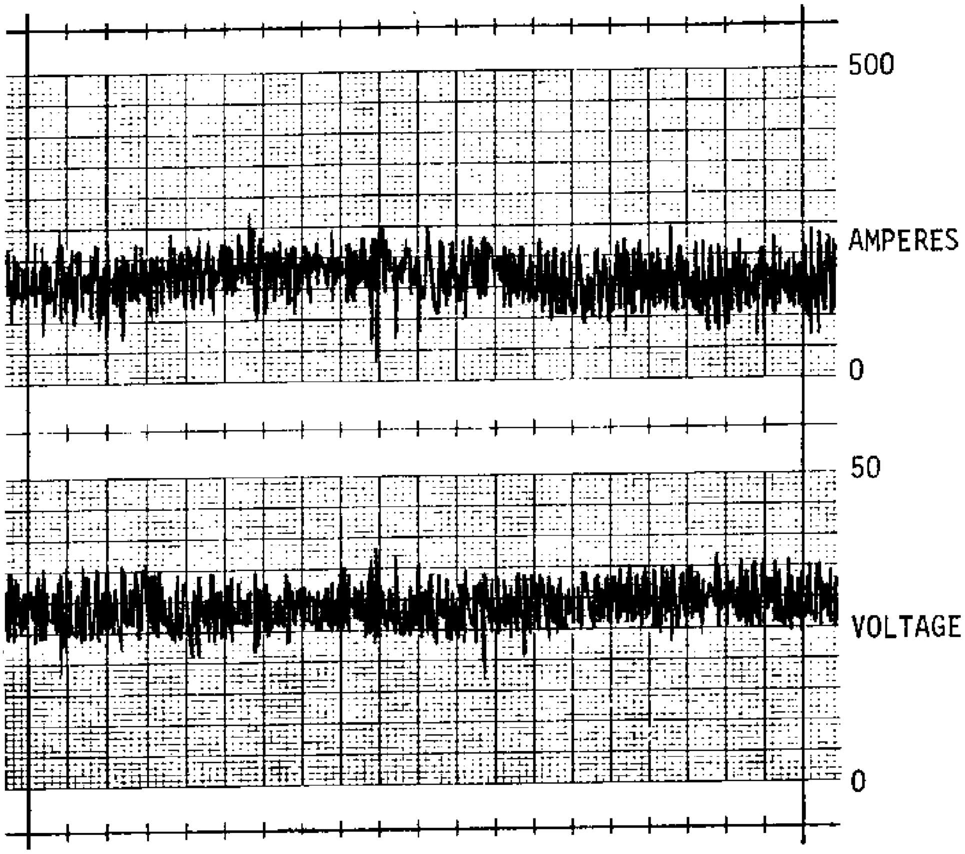


FIGURE 5-2 Voltage-current trace for flux-shielded process at 200 psig

5.2.3 Metallurgical Test Results

The welds made at different pressures using the GMA and the FSA processes were sectioned and examined for the following properties:

(a) Weld bead appearance and defects

(b) Penetration

(c) Hardness

1. Weld Bead Appearance and Defects. The macrostructures of the weld were examined for the shape of the weld bead and defects, such as cracks, lack of fusion, undercut, etc. Figure 5-3 defines the different terms used to describe the bead shape and Table 5-4 gives the results of the measurements.

2. Penetration. The welds made by the GMA process had a larger penetration compared to those by the FSA process at a given pressure. The penetration did not change with an increase in pressure for GMA welds. In the case of FSA welds no such conclusion could be made.

3. Hardness. Microhardness values of the weld metal, HAZ and base metal were measured for welds made by the GMA and FSA processes at different pressures. The results are given in Table 5-5. From the limited number of experiments carried out, we see that the hardness of the weld metal and the heat affected zone increased with an increase in pressure. The hardness values of the weld metal and HAZ were lower for the FSA welds compared to the GMA welds made at a certain pressure level.

5.3 Erickson's Study on Effects of Pressure on Flux-Shielded Arc Welding Underwater

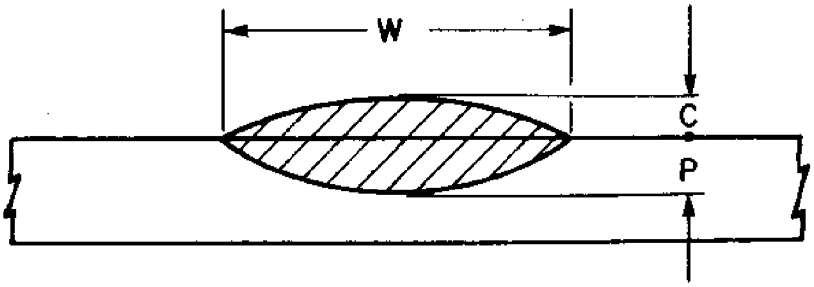
Erickson [T15] studied the effect of pressure on flux-shielded arc welding.

TABLE 5-4 Effect of pressure on weld bead shape

Pressure	Gas metal arc welds		Flux-shielded welds	
	W/P	C/W	W/P	C/W
Atmospheric	3.48	0.40	7.20	0.36
50psig	2.67	0.63	9.42	0.39
100spig	2.83	0.59	19.67	0.44
150psig	3.50	0.52	9.85	0.39
200psig	4.62	0.47	6.17	0.36
280psig	3.39	0.49	7.17	0.31

TABLE 5-5 Effect of pressure on the weld and the heat affected zone hardness

Pressure	Knoop hardness					
	Gas metal arc welds			Flux-shielded welds		
	Weld Metal	H A Z	Base Metal	Weld Metal	H A Z	Base Metal
Atmospheric	227.0	264.6	181.5	224.4	249.0	179.7
50psig	258.2	312.0	181.5	281.4	237.8	191.6
100psig	246.2	277.8	179.7	316.2	237.8	179.7
150psig	252.0	281.4	179.7	300.0	232.2	179.7
200psig	258.2	300.0	179.7	267.8	227.0	179.7
280psig	258.2	300.0	187.1	288.6	229.6	179.7



W	**BEAD WIDTH**
C	**CONVEXITY**
P	**PENETRATION DEPTH**
R	**BEAD WIDTH/ PENETRATION DEPTH**
S	**PENETRATION DEPTH / BEAD WIDTH**

FIGURE 5-3 Definition of bead shape

5.3.1 Experimental Procedure

Figure 5-4 shows the experimental setup. Underwater welding was performed by placing a plexiglass tank containing water inside the chamber and pressurizing the chamber by means of air compressor to the desired pressure. Specimens to be welded were immersed in water but the welding equipment was not in water. The plexiglass tank was filled with water to a depth of 5 to 6 inches.

To simulate a flux cartridge for the experimental investigation a container was constructed which could be attached to a plate by the use of small studs, as shown in Figure 5-4. The container served to hold the flux in position and to isolate the flux from the surrounding water

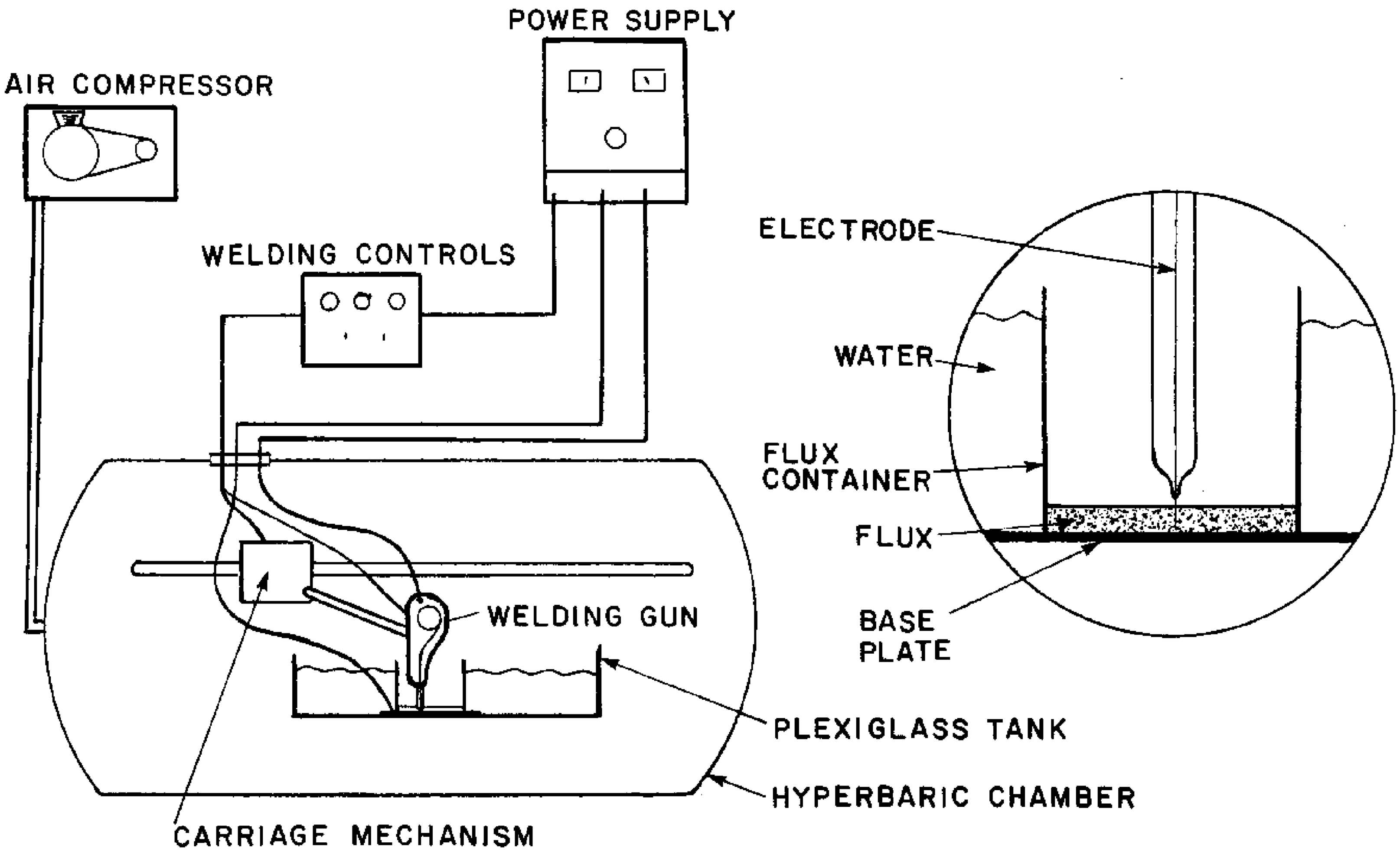


FIGURE 5-4 Schematic diagram of experimental setup

during welding. The top of the container was open to the pressurized air atmosphere to enable the welding electrode to traverse along the plate.

Bead-on-plate welds were made on cold rolled low-carbon steel plates 1/4 inch thick. The plates were 6 inches wide by 10 inches long with the weld being made longitudinally along the centerline. Mild steel welding wire of 0.030 inch diameter was used for all welds made. The wire feed set was at 12.5 feet/minute for all welds. Travel speed was set at 9 inches/minute. The weld beads varied in length from 6 to 7 inches. The weld area was protected by a 3/4 inch layer of Lincoln Flux No. 710 held by the flux container.

Welds were performed underwater in tap water at 0, 50, 100, 150, 200, 250, and 300psig pressure corresponding to 0, 114, 227, 340, 455, 570, and 680 feet, respectively, of water depth. The welds were performed using reverse polarity. The potential setting of the power supply was increased slightly with increasing pressure to obtain welds which are similar in appearance and quality for the various pressures. Arc voltage and welding current were continuously recorded during welding. Five Chromel-Alumel thermocouples were attached to the surface of each steel plate as shown in Figure 5-5. The distance from the weld beads varied slightly from weld to weld due to slight differences in alignment of electrodes from weld to weld.

An additional weld was made at 0 psig with flux which was damp. This weld was made in order to demonstrate one of the limitations of the method discussed later.

5.3.2 Computer Heat Flow Analysis

Tsai [T13,P17,P18] developed a semi-empirical computer analysis of heat flow in underwater welding. Since his study was not directly connected with this research program a paper, based on his Ph.D. thesis, entitled "Mechanisms of Rapid Cooling and Their Design Considerations in Underwater Welding" is included as APPENDIX C. The analysis shows the

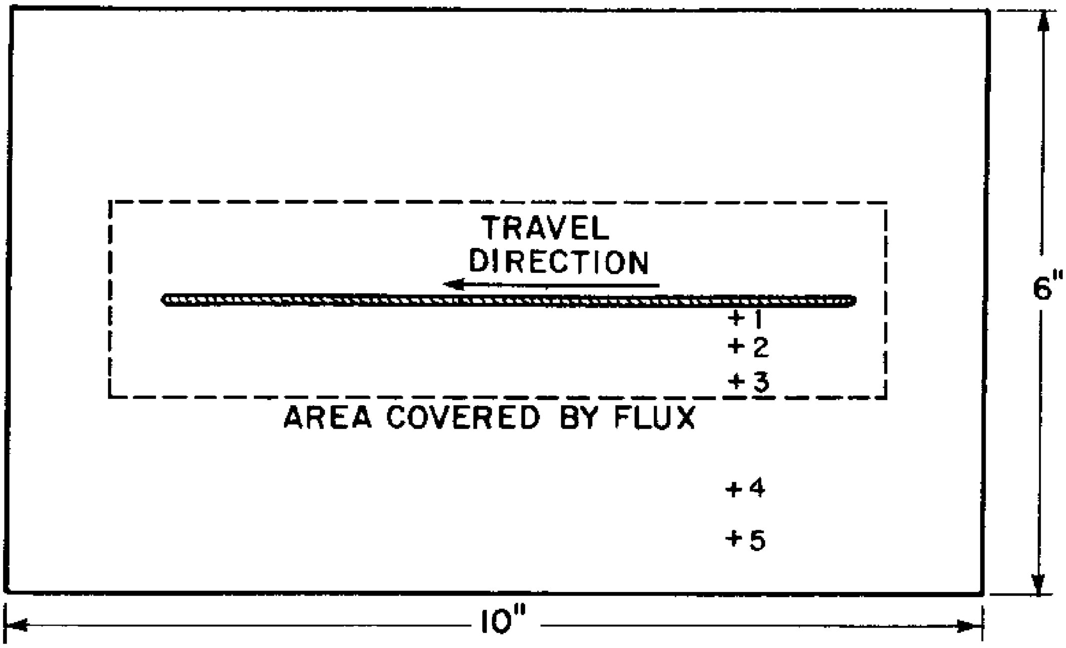


FIGURE 5-5 Thermocouple location on welding plate

effectiveness of the flux-shielded process in reducing cooling rate during underwater welding. Figure 11 of APPENDIX C shows that:

> "The cooling rate during underwater FSA welding is much slower that that of wet SMA welding and it is almost as slow as that of air welding. While HAZ structures in wet SMA welding are completely martensitic, no martensitic structures would be produced in FSA welds in 0.17% carbon steel."

The most effective way in reducing cooling rate during underwater welding is to separate the molten weld metal from surrounding water, as it was dicussed in an earlier Sea Grant report [P13]. And flux shielding is a very effective method of accomplishing this.

The computer programs developed by Tsai were used to analyze the experimental results obtained by Erickson.

5.3.3 Experimental Results and Discussion

A summary of the welding parameters and experimental results of the underwater flux-shielded welds performed is presented in Table 5-6.

TABLE 5-6 Summary of welding parameters and results for experimental underwater flux-shielded welds.

Pressure [psig]	Equivalent Water Depth [ft]	Arc Voltage [volts]	Arc Current [amps]	Arc Power joule [sec]	Bead Width [cm]	Bead Penetration [cm]	$\frac{\text{Bead Width}}{\text{Bead Penetration}}$
0	0	32	110	3520	0.655	0.135	4.85
50	113	26	140	3640	0.800	0.140	5.71
100	226	29	130	3770	0.685	0.150	4.57
150	340	31	170	5270	0.810	0.250	3.24
200	453	30	140	4200	0.735	0.090	8.17
250	567	31	160	4960	0.895	0.200	4.48
300	680	30	170	5100	0.880	0.225	3.91
0 Damp Flux	0	32	110	3520	0.680	0.100	6.80

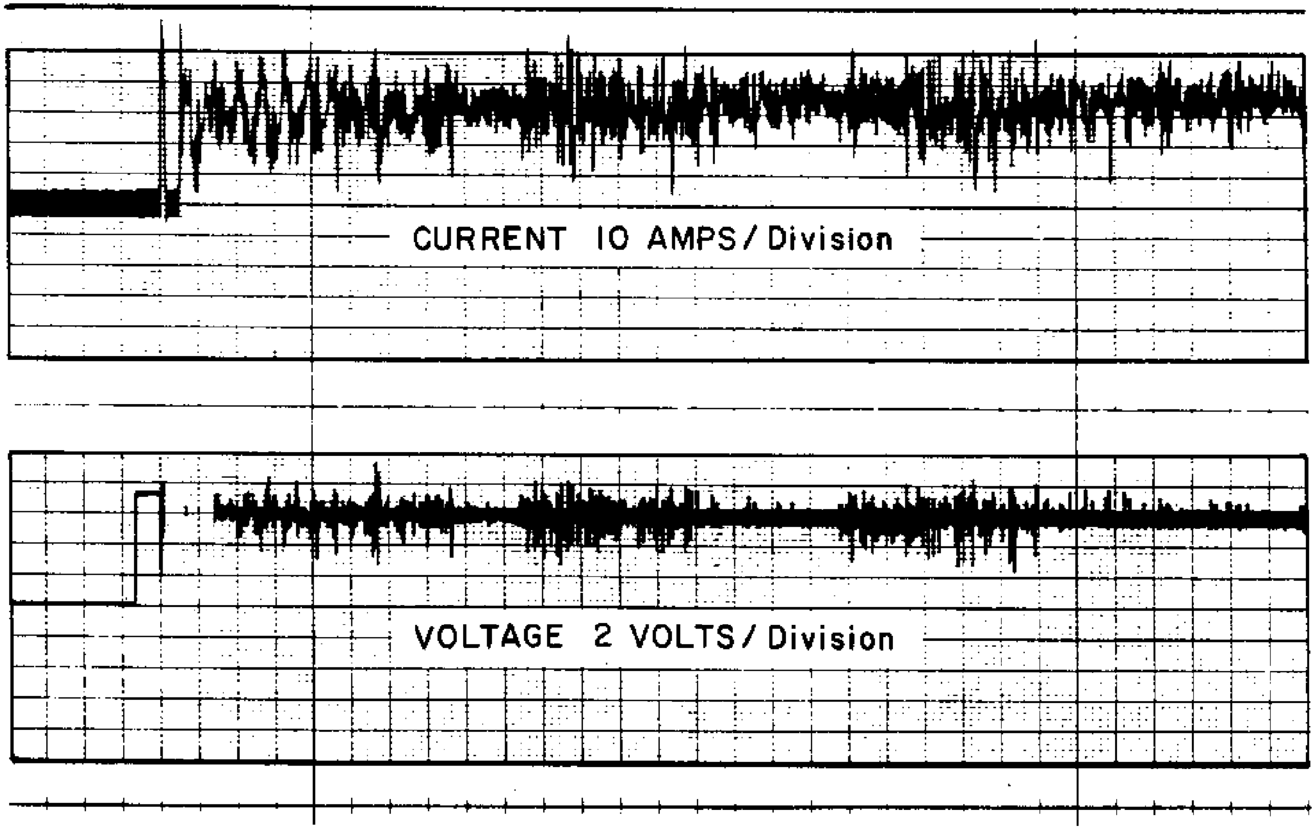


FIGURE 5-6 Voltage and current traces for underwater flux-shielded weld (300 psig)

Shown here are welding conditions and bead width, bead penetration, and the ratio of bead width to bead penetration. The penetration tended to increase and the ratio of bead width to penetration tended to decrease as the arc power increased.

Figure 5-6 shows the voltage and current traces for the underwater welding arc at 300psig. Very similar traces were produced for the other welds performed. A steady arc could be produced and maintained during welding regardless of the pressure. The arc power for the weld performed at 150psig was higher than expected for no apparent reason.

Figures 5-7 and 5-8 show microhardness distributions of welds made at 0 and 300psig, respectively. Examination of microstructures revealed no martensitic structures in all of the welds made. Welds were free from defects such as inclusions, porosity, and cracks.

Figures 5-9 and 5-10 show temperature profiles predicted by the computer analysis and experimental data for welds made at 0 and 300psig, respectively. In the computer analysis it was assumed that the flux shielding provides a perfectly insulated layer of flux 2.5 inches wide. Heat transfer to the water was assumed to be natural convection from a horizontal plate. Although there were some differences between the experimental data and analytical predictions, the temperatures and times were of the same order indicating that the computer analysis is reasonably valid in predicting heat flow in weldments.

All the welds discussed above were for the FSA method with dry flux. One weld was made at 0 psig with damp flux to illustrate the limitation of the method. The weld metal contained large slag inclusions and a good deal of porosity. No cracks were found however. Figure 5-11 shows microhardness readings of the weld. Higher hardness readings were observed in the weld metal for the damp flux weld than for any of the dry flux welds indicating that the presence of the moisture may have affected the metallurgical structures of the weld metal. This weld made with damp flux demonstrates that the weld metal must remain dry if good quality

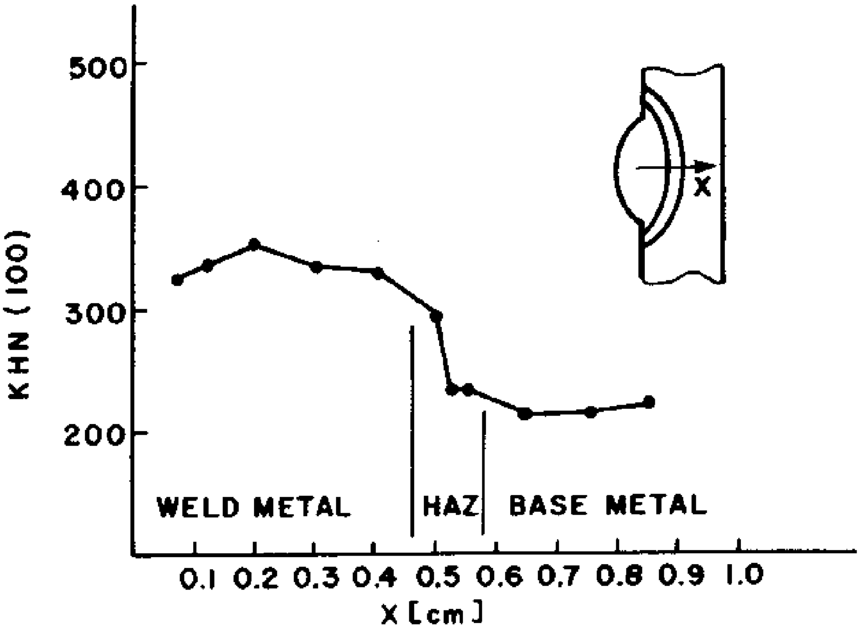


FIGURE 5-7 Microhardness readings in underwater flux-shielded weld (0 psig)

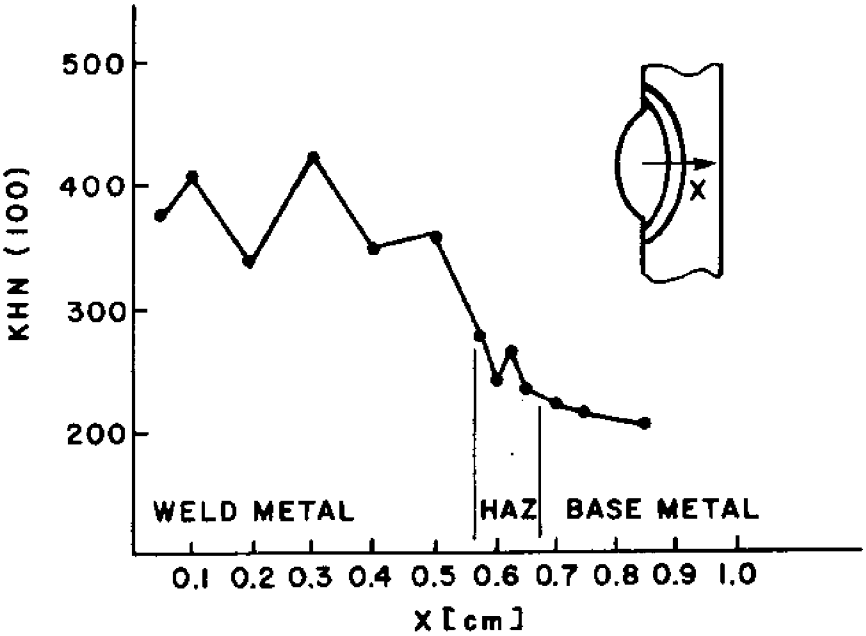


FIGURE 5-8 Microhardness readings in underwater flux-shielded weld (300 psig)

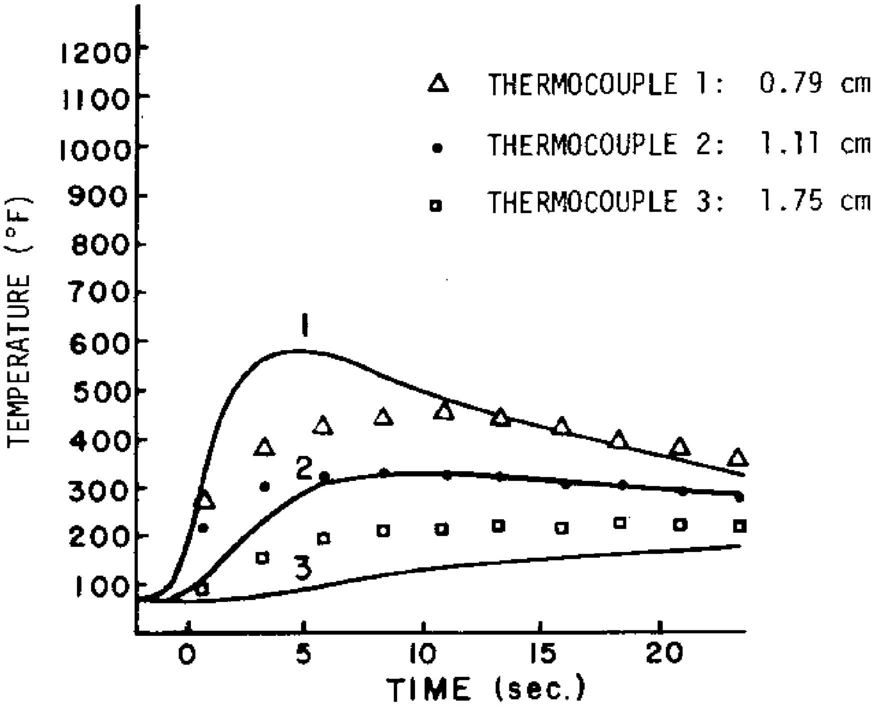


FIGURE 5-9 Calculated temperature amd measured temperature in underwater flux-shielded weld (0 psig)

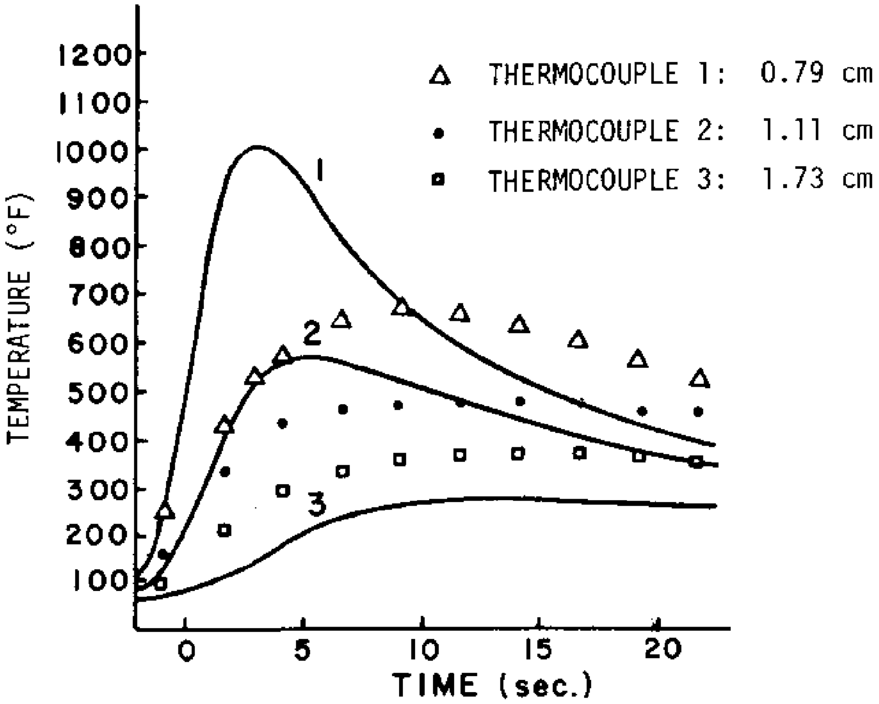


FIGURE 5-10 Calculated temperature and measured temperature in underwater flux-shielded weld (300 psig)

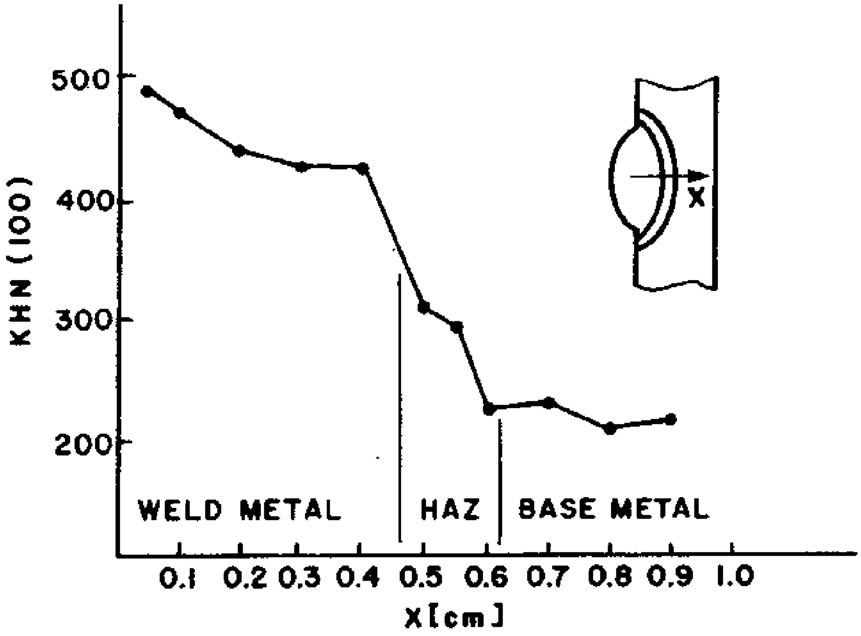


FIGURE 5-11 Microhardness readings in underwater flux-shielded weld with damp flux (0 psig)

welds are to be obtained.

5. 4 Summary and Conclusion of Task 3

(1) It was demonstrated that the deep-sea underwater welding simulation facility installed at M.I.T. works satisfactorily. Welds were made automatically by merely pressing an appropriate button on the control device outside the presence tank. Welds were made using gas metal-arc and flux-shielded arc processes in dry and wet conditions at pressures up to 300psig which corresponds to 700 feet deep water.

(2) Prasad studied effects of pressure on GMA and FSA welds in dry environment. He examined the pressure effects on various subjects including welding parameters, weld bead appearance and defects, penetration, and hardness. The test conditions were rather limited, however. Additional tests are needed to make conclusive statements on the pressure effects.

(3) Erickson studied effects of pressure on FSA welds underwater. The most important conclusion of his work was that it demonstrated that the flux-shielded process is a very promising technique to be used for deep-sea applications. Welding arcs were metallurgically sound. Hardnesses of the weld metal and HAZ were not very high and no martensitic structures were observed. In order to produce sound welds it is important to keep the flux dry. Erickson examined the pressure effects on various subjects including welding parameter, weld bead appearance and defects, penetration, hardness, and heat flow characteristics. The best conditions were limited however. Additional tests are needed to make conclusive statements on the pressure effects.

CHAPTER 6

DEVELOPMENT AND TESTING OF STUD WELDING SYSTEMS

M.I.T. researchers became interested in underwater stud welding in 1974. During the second Sea Grant supported research program entitled "Development of New, Improved Techniques for Underwater Welding", Professor K. Masubuchi and Dr. M. Kutsuna thought that stud welding could be done successfully underwater [P13]. They filed an application of a U.S. patent on underwater stud welding gun. The U.S. patent #3,989,920, granted in November, 1976, is included in this report as APPENDIX A-1. Under their guidance Zanca [T8] wrote a thesis on underwater stud welding.

During this research program on deep-sea underwater welding, M.I.T. researchers believed that the stud welding is a good process to be used for deep-sea underwater applications. Studies were made primarily by two graduate students Chiba [T12] and Kataoka [T17]. Two undergraduate students Schechter [T19] and Nakagawa also provided contributions.

6.1 Stud Welding Process

Stud welding is an arc welding process in which metal studs or similar parts and a work piece are heated and melted by an electric arc drawn between them. Then the two pieces are brought together under pressure to form a welded joint. This simple joint replaces drilled-and-tapped studs, reduces the number of required operations, and saves time and money. According to Houldcroft [C32] the arc stud welding process was invented by H. Martin and used from 1918 by the British Royal Navy but the process was not widely known until it was rediscovered by E. Nelson in the U.S.A. twenty years later.

The two basic techniques of stud welding are defined by their method of power supply. A motor generator, a transformer rectifier, or a storage battery must be used as a power supply for the first method, arc stud welding. The power supply for the second method, capacitor-discharge stud welding, is a low-voltage electrostatic storage system, and the arc is produced by a rapid discharge of stored electrical energy. Both methods involve direct current and arcing and in both cases the stud serves as the electrode and a "stud gun" as the electrode holder.

6.1.1 Arc Stud Welding [P13, C33, C34]

Above water, the arc stud welding process is the most widely used of the two basic types of stud welding and is similar in many respects to the shielded metal-arc welding. The equipment consists of the stud gun, a control unit (timing device), studs and ferrules, and an available source of d.c. welding current. Figure 6-1 shows a typical setup for arc stud welding [C33].

The mechanics of the process are illustrated in Figure 6-2 [C33]. The stud is loaded into the chuck, the ferrule (also known as an arc shield) is placed in position over the end of the stud, and the gun is properly positioned for welding (Figure 6-2A). The trigger is then depressed, starting the automatic welding cycle (Figure 6-2B). The stud is lifted by a solenoid within the body of the gun, creating an arc and forming a molten pool on the work piece and the stud end. A controlling device limits the arc period automatically, according to a predetermined setting. At the end of the arcing period, the welding current is shut off, de-energizing the solenoid, allowing the mainspring of the gun to plunge the end of the stud into the small volume of molten metal to complete the weld cycle (Figure 6-2C). The gun is then lifted from the stud and the ferrule is knocked off since the weld solidifies almost instantly (Figure 6-2D). A shielding gas is sometimes used when nonferrous alloys are being arc stud welded.

The weld is usually completed in less than one second, the actual duration of the weld cycle depending upon the diameter of the stud and the particular equipment used. By using a ceramic arc shield (ferrule) around the stud, substantial shielding is obtained while retaining the molten metal to form a fillet weld. Apart from shaping the fillet, the

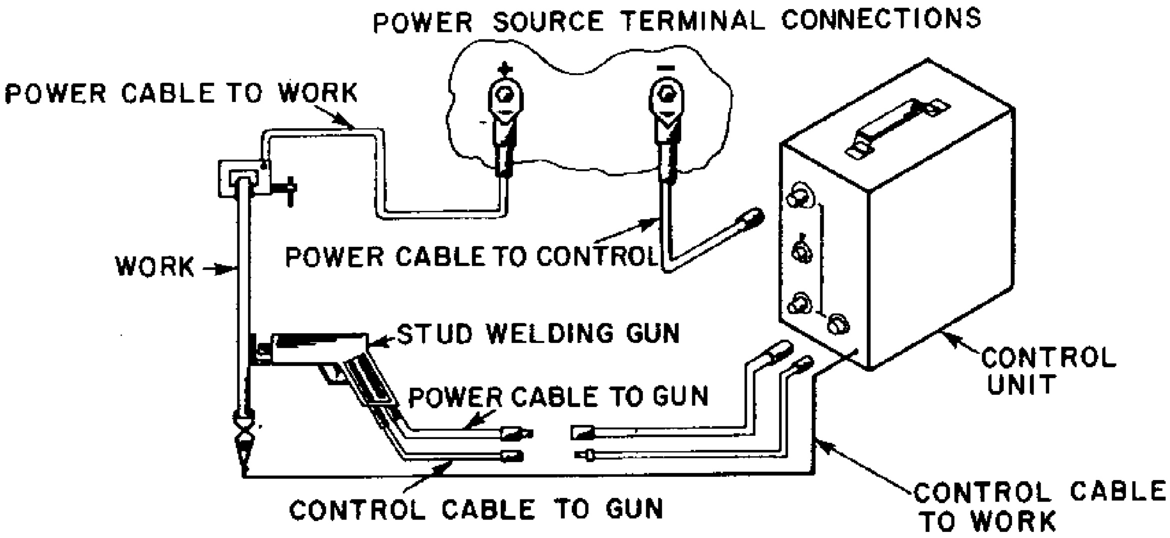
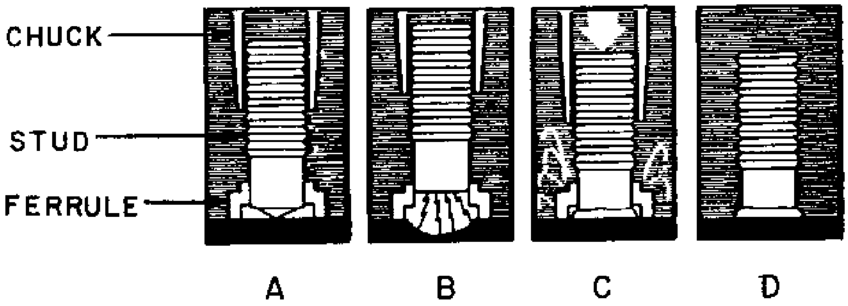


FIGURE 6-1 Equipment setup for arc stud welding [C33]



A Gun is properly positioned

B Trigger is depressed and stud is lifted, creating an arc

C Arc period is completed and stud is plunged into the molten pool of metal on the base metal

D Gun is withdrawn from the weld stud and the ferrule is removed

FIGURE 6-2 Steps in arc stud welding [C33] ferrule shields the operator from the glare of the welding arc and when preplaced in jigs, it helps in the positioning of the stud. Flux is generally used for arc stud welding, since it provides a cleaning action and acts as an arc stabilizer and deoxidizing agent.

The arc stud welding process is most effectively used when the base metal is thick enough to enable the weld to be made without burn-through and allowing the full strength of the welded stud to be developed. For low-carbon steels, the weld base diameter of the stud should be at least one-third the base metal thickness, and, to avoid burn-through, the weld base diameter should be at least one-fifth of the base metal thickness.

6.1.2 Capacitor Discharge Stud Welding [P13, C33, C34]

The second basic stud welding process derives its heat for welding from an arc produced by a rapid discharge of stored electrical energy, with pressure applied to the stud during or immediately following the electrical discharge. There are three different types of capacitor discharge stud welding:

(1) Initial contact

(2) Initial gap

(3) Drawn arc

The arc is established either by rapid resistance heating of a projection on the stud weld base with a resulting weld time of 3 to 6 milliseconds, or by drawing the arc in a similar manner to that of arc stud welding by lifting the stud away from the plate. The latter procedure results in a 6 to 15 millisecond weld time. In either case, no ceramic ferrule or flux is used due to the speed of welding.

Another consequence of the extremely short welding time in capacitor discharge stud welding is the absence of heat build-up. This allows welding of studs to thin materials without pronounced distortion, burn-through, or discoloration. Weld penetration is slight, which permits many dissimilar metals to be welded with acceptable strength and metallurgical structure.

In the initial study at M.I.T. on underwater stud welding a capacity discharge type machine was used, because it was the only machine available at M.I.T. at that time. Experiments were conducted on small studs 1/8-inch in diameter. In later studies, however, all experiments were made on large studs 1/2 to 3/4 inch in diameter using an arc stud type machine. Therefore, no further discussion on the capacity discharge stud welding is given here.

6.2 Underwater Applications of Stud Welding

6.2.1 Historical Development

Although stud welding had been used in shipbuilding and other construction industries since around 1920, no investigator was seriously interested in its underwater applications until M.I.T. researchers became convinced in 1974 that stud welding could be done successfully underwater. Under the guidance of Masubuchi and Kutsuna, Zanca [T8] wrote a thesis on underwater stud welding. He used a capacity discharge type stud welding gun available at M.I.T. at that time. Because of the capacity limitation of the equipment, experiments were made of small studs 1/8 in. diameter. It was found that stud welding could be made successfully underwater. The results are reported in the second Sea Grant report on underwater welding, MITSG 77-9 [P13]. In 1976 a U.S. patent on underwater stud welding gun was granted to Masubuchi and Kutsuna [P11].

This M.I.T. effort apparently raised interest of investigators in other laboratories. In 1976 a research program on underwater stud welding was started at the Technical University of Delft, the Netherlands [C35]. The study included experiments performed in the sea [C36]. Hamasaki and Tateiwa [C37] of Japan reported in 1979 that they had developed an underwater stud welding gun.

Representatives of several companies have expressed to M.I.T. researchers their interest in using stud welding for various undersea construction works. However, M.I.T. researchers know no examples of large-scale applications of stud welding underwater.

6.2.2 Efforts in This Research Program

M.I.T. investigators decided to select stud welding as one of the two processes to be studied in depth in Tasks 4 through 7. Major reasons for making this decision are described below.

Firstly, M.I.T. researchers believed that there is a need for developing joining techniques other than dry chamber arc welding processes. As stated earlier, it is possible to use dry chamber arc welding processes in deep sea as long as a proper diving system is developed. However, dry chamber processes are extremely expensive. As far as mechanisms of welding are concerned dry chamber arc welding processes are not very different from ordinary land welding, except pressures are high in hyperbaric welding. There are many cases in which dry chambers cannot be used or they are too expensive to use.

However, uses of simple "wet" SMA and GMA processes in deep sea will be severely limited. Normal arc welding requires considerable skill in manipulating the electrode or the welding gun. It becomes extremely difficult to perform necessary electrode manipulation in deep sea. The use of gas metal arc in deep sea is impractical, if not impossible, because it becomes extremely difficult to provide shielding of the welding arc by gas.

The stud welding process is suited for underwater applications for the following reasons:

(1) Stud welding requires no skill. It is possible to develop a complete welding system which can be activated by merely pressing a button or the system can be activated remotely.

(2) Considerable portions of the welding system can even be flooded with water.

Studies in underwater stud welding were conducted primarily by the following students:

Jun-ichi Chiba

Toshioki Kataoka

Peter C. Schechter

Roy Y. Nakagawa

Mr. Chiba and Mr. Kataoka wrote theses. Mr. Schechter prepared a report. Their results are presented in this report. Although their studies covered Tasks 5, 6, and 7, results obtained by individual investigators are presented in this report.

The investigation on underwater stud welding is still being continued by Mr. David W. Schloerb. Experiments in actual diving conditions are also being planned. Results of this continuing study will be included in a future report covering the current research entitled "Development of Instamatic Systems for Marine Applications".

6.3 Study by Chiba [T12, P16]

In the earlier study conducted during the 1974/75 academic year, experiments were conducted using a capacity discharge type stud welding equipment available at M.I.T. at that time. Underwater welds were successfully made using small studs 1/8 inch (3.2 mm) diameter. Results were reported in Zanca's thesis [T8] and the second Sea-Grant report on underwater welding [P13].

During the 1976/77 academic year a study was made to investigate whether underwater welds could be successfully made using large studs up to 3/4 inch (19 mm) in diameter. The KSF Fastening Systems Division was kind enough to loan, at no cost to M.I.T., a complete set of arc stud welding equipment. Details of the investigation were reported in Chiba's thesis [T12]. A paper which summarized the results was presented by Masubuchi, Ozaki, and Chiba at the Oceans '78 Conference [P16].

6.3.1 Experimental Conditions

Figure 6-3 shows schematically the experimental setup. The power house, or stud welding machine, is a transformer-rectifier type welding power supply which can be used for both stud welding and ordinary shielded metal arc using covered electrodes. An arc stud welding gun designed for air use was used in the experiment. Since the gun was not made watertight, the gun was not immersed in water. In conducting a welding experiment underwater, the specimen was placed in a tank containing tap water. Limited experiments using actual sea water revealed little difference in weld appearance from that made using tap water.

Low-carbon steel studs were used for both low-carbon steel and HY-80 steel base plates 1/2 inch to 1 inch thick. The stud diameter was 3/4 inch, and the weld base diameter was 0.684 inch. The stud was 2.75 inch long before welding, and 2.5 inches after welded. Welds were made under three conditions as follows:

1. Air welding with dry surface
2. Air welding with wet surface
3. Underwater welding

In an initial study, it was found that arc initiation underwater was very difficult. Even in welding on a wet surface it was found to be more difficult to initiate the arc than welding on a dry surface. An effort was made toward finding ways of initiating a stable arc underwater. A method which was found to be effective was to place a small amount of steel wool or an aluminum foil between the tip of the stud and the workpiece. Steel wool was used throughout the experiment. Studs could be successfully welded in sea water. It was found that successful welds could be made in water 4 inches deep.

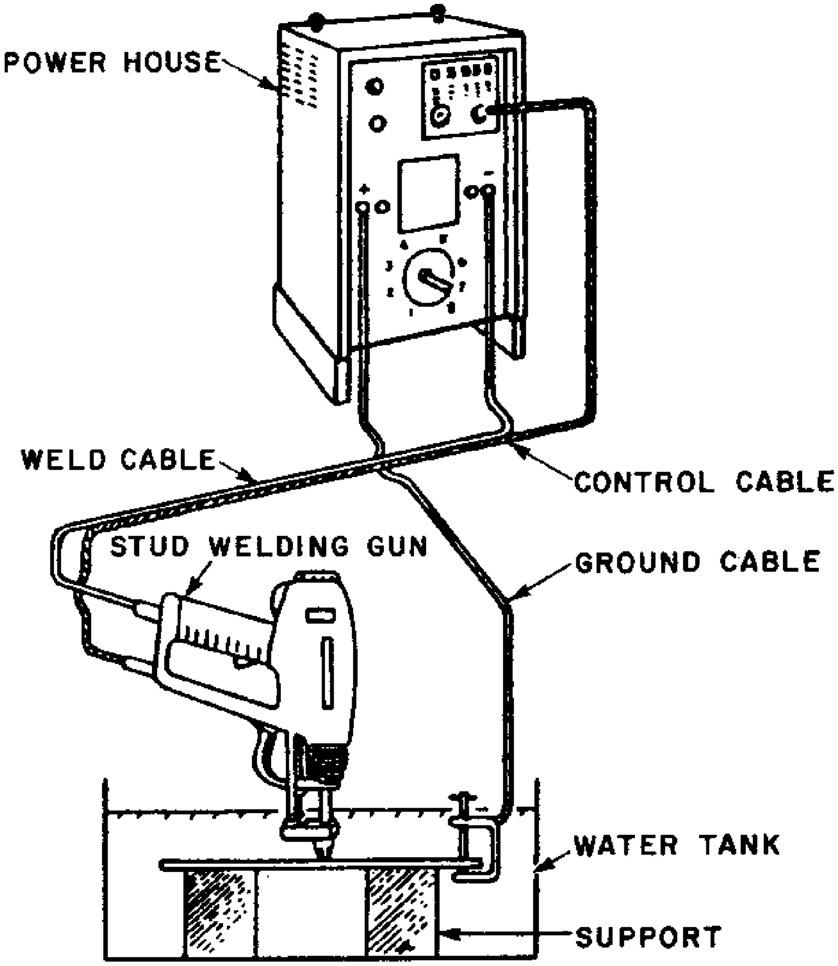


FIGURE 6-3 Arc stud welding setup used by Chiba

The optimum welding periods for air welds and wet surface welds were approximately 0.6 to 0.9 second. For underwater welding 1 inch deep it was 0.7 to 0.85 second. In both cases, the welding current was set to 1,750 amperes, which was recommended by the manufacturer for air welding. When the welding time was too short (0.5 sec.) an extremely "cold" weld was the result. A welding time of 0.9 second gave an excessively "hot" weld. The welding time had a significant influence on the weld quality. Figures 6-4, 6-5 and 6-6 show some defective welds. Shown here are cross sections of stud welded specimens. For each test conditions welding parameters were selected to produce good welds.

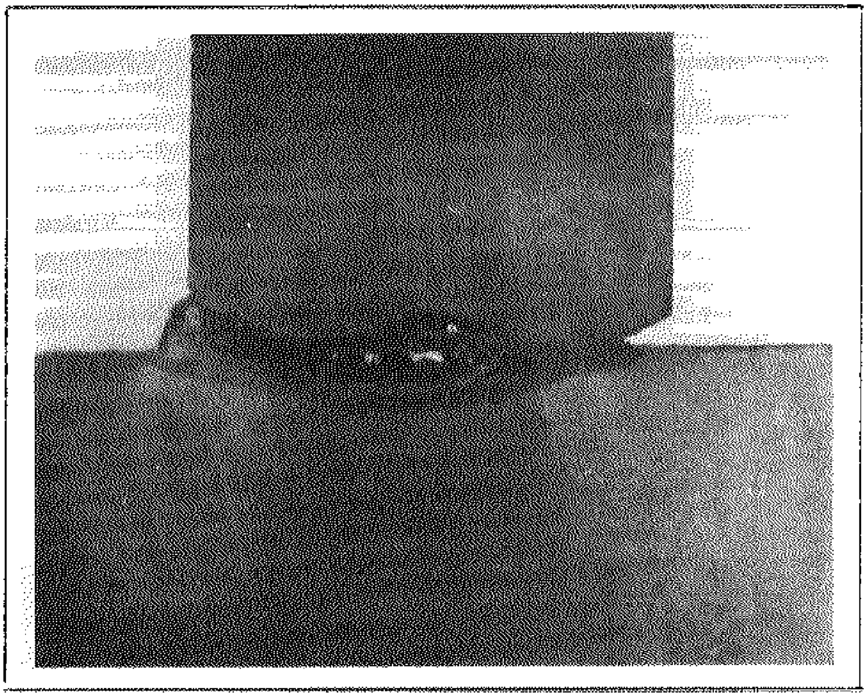


FIGURE 6-4 Weld defect --- Extremely cold weld
Underwater 1 in. depth --- Mild steel base plate
(X3.7, 1% nital etch)

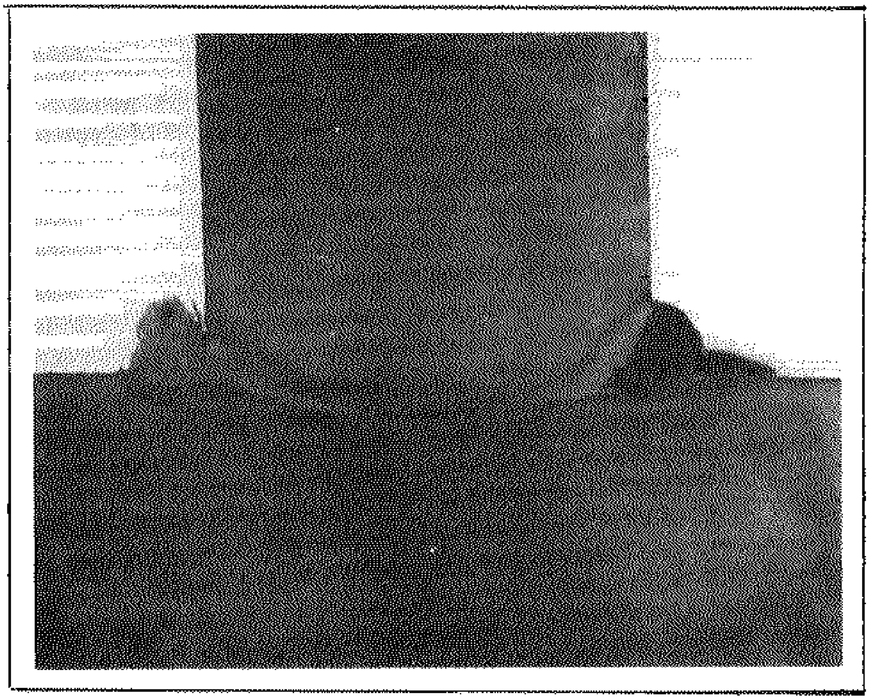


FIGURE 6-5 Weld defect --- Cold weld
Underwater 1 in. depth --- Mild steel base plate
(X3.5, 1% nital etch)

Further mechanical and metallurgical tests were made mostly welds made using the optimum welding parameters.

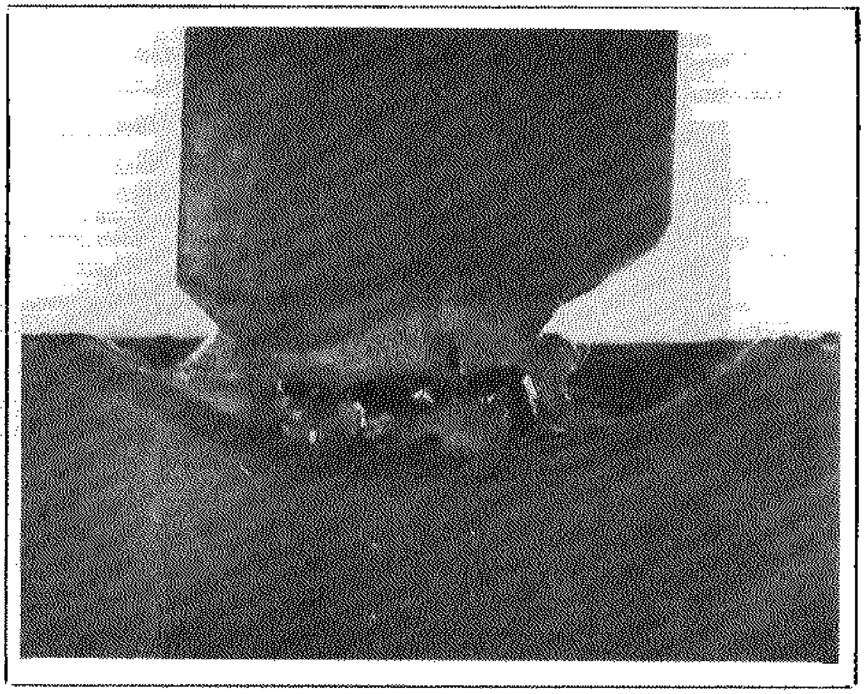


FIGURE 6-6 Weld defect --- Extremely hot weld
Underwater 1 in. depth --- Mild steel base plate
(X3.8, 1% nital etch)

6.3.2 Mechanical and Metallurgical Tests

(1) Tensile Tests. Tensile test specimens were prepared by welding studs on both sides of the plate. The specimen was set between the threaded chucks by a Baldwin hydraulic testing machine, which provided a slow, steady tensile loading to the test specimen. The test on each specimen was run until either stud fractured, giving the ultimate strength of the weld, or the weld fractured, indicating an insufficient fusion in the weld joint.

Table 6.1 gives the tensile test results of the welded stud specimens. Two specimens were prepared from both air welding and wet-surface welding. These specimens were prepared for underwater welding 1 inch deep. All of the specimens were welded under optimum conditions. The same results are plotted in Figure 6-7 for quick reference. All specimens, except #3 (wet-surface weld), fractured at threaded portion of the studs, giving the ultimate tensile strength of the stud. Figure 6-8 shows a typical fracture which occurred at the threaded portion of the stud. Specimen #3 fractured in the stud along the heat-affected zone of the weld, as shown in Figure 6-9. The fractured surface revealed insufficient fusion. From the tensile test results, it was concluded that underwater stud welds with the quality of an air weld could be obtained by carefully applying a steel wool arc initiator. A 3/4-inch diameter stud can hold a tensile load of approximately 10 to 12 tons.

(2) Bend Tests. A simple bend test was devised to provide information about the weld quality. A test pipe four feet long was used for bending studs. Although no bending load was recorded, their simple bend test was adequate in that the soundness of the welded joint could be quickly examined. Studs that fractured in the weld metal or the heat-affected zone were considered unsuitable for usage. This type of test is easily carried out at the job site by an operator, and can be used to test welded studs when any change of welding conditions is made.

Figure 6-10 shows an example of a specimen subjected to the bend test. The specimen fractured along a thread of the stud. The bend test results showed that welds were sufficiently strong.

(3) Macroscopic Examinations. Macroscopic examinations were made of specimens prepared from some welded samples to study how welds were made. Figures 6-11 through 6-16 show cross sections of stud welded specimens made under various test conditions. Some were made underwater, while others were made in air or with wet surfaces; some welds were made on low-carbon steel plates, while others were made on HY-80 steel plates.

Table 6-1 TENSILE TEST RESULTS OF WELDED STUD SPECIMENS

SPECIMEN	CONDITION	ULTIMATE TENSILE STRENGTH lbs per stud (metric ton)	 ksi (kg/mm^2)
1	AIR WELD	2.82×10^4 (12.79)	76.74 (53.97)
2	AIR WELD	2.65×10^4 (12.02)	72.12 (50.72)
3	WET SURFACE WELD	$^*2.58 \times 10^4$ (11.68)	70.08 (49.29)
4	WET SURFACE WELD	2.72×10^4 (12.34)	74.02 (52.07)
5	UNDERWATER 1 in. DEPTH	2.70×10^4 (12.25)	73.48 (51.69)
6	UNDERWATER 1 in. DEPTH	2.70×10^4 (12.25)	73.48 (51.69)
7	UNDERWATER 1 in. DEPTH	2.72×10^4 (12.34)	74.02 (52.07)

NOTE: Stud diameter -- 3/4 in. Weld base diameter -- nom. 0.684 in.

*-- HAZ portion of the stud side fractured.

Other specimens, threaded portion of the studs fractured.

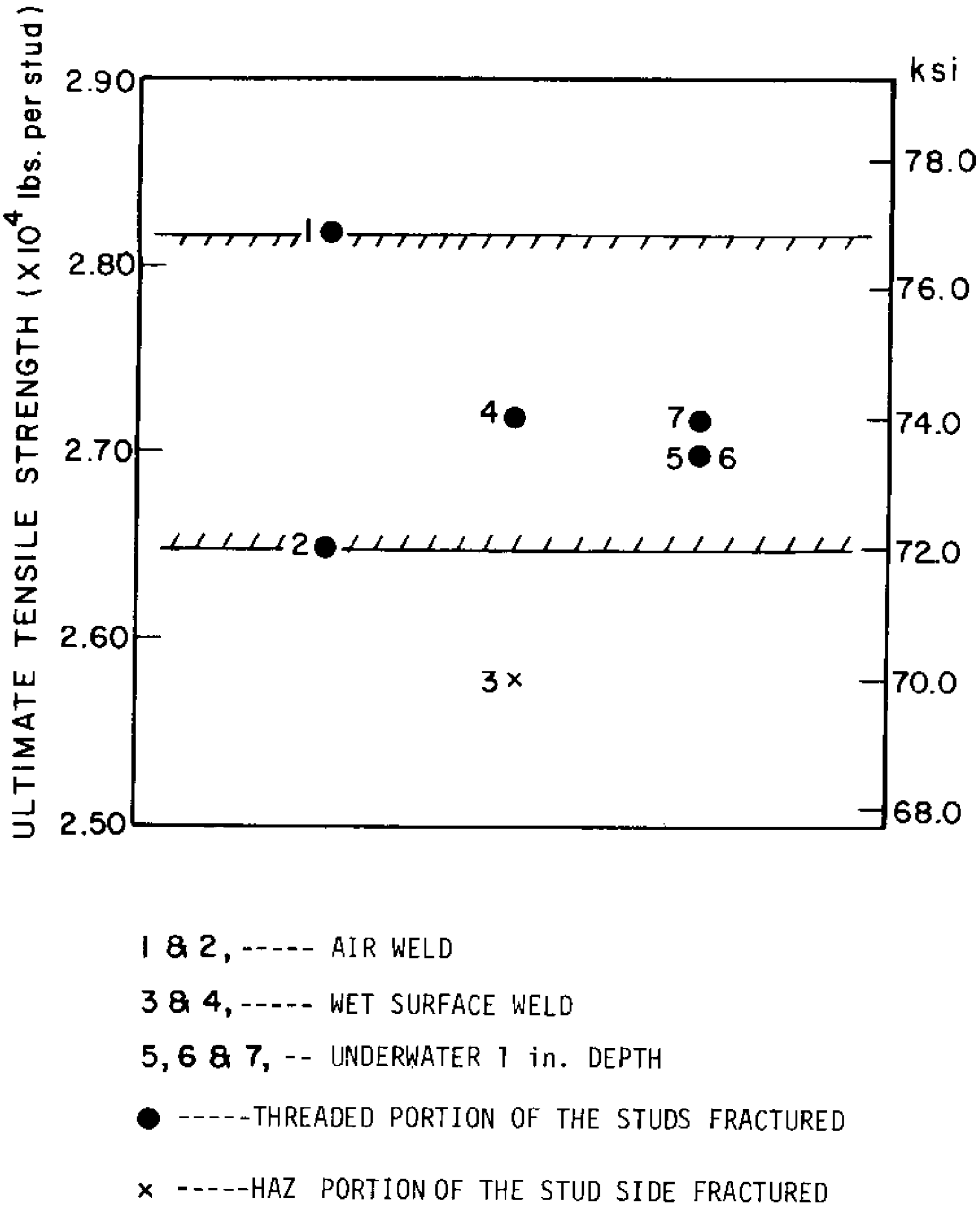


FIGURE 6-7 Tensile test results of welded stud specimens

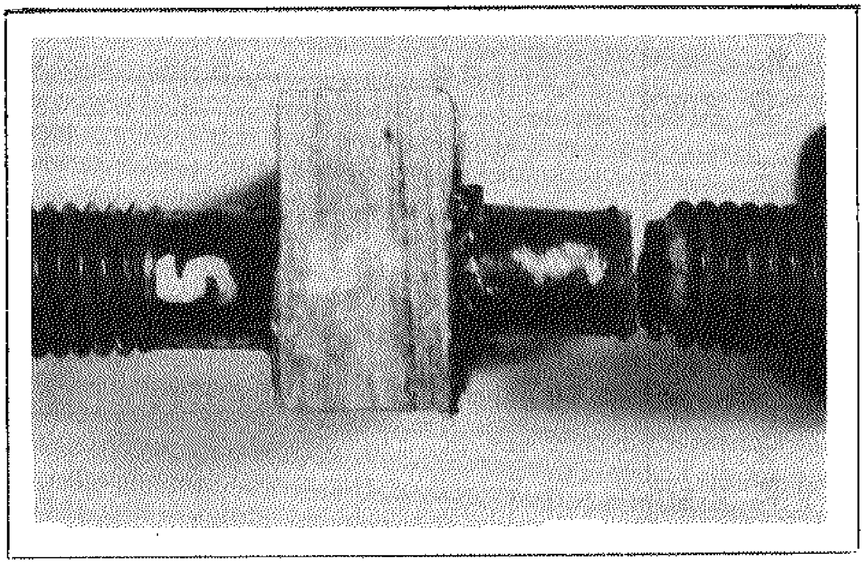


FIGURE 6-8 Appearance of tensile tested specimen
Underwater 1 in. depth --- Mild steel base plate

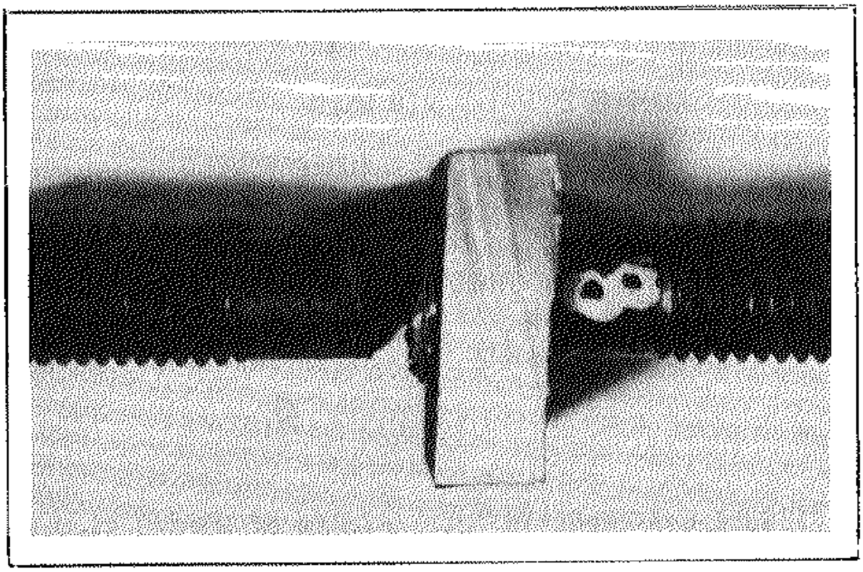


FIGURE 6-9 Appearance of tensile tested specimen
Wet surface weld --- Mild steel base plate

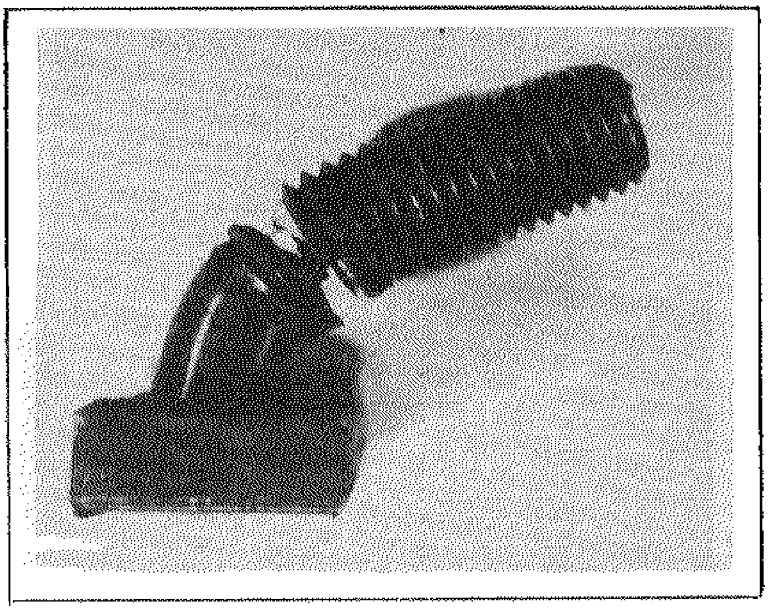


FIGURE 6-10 Appearance of bend test result
Underwater 1 in. depth --- Mild steel
base plate

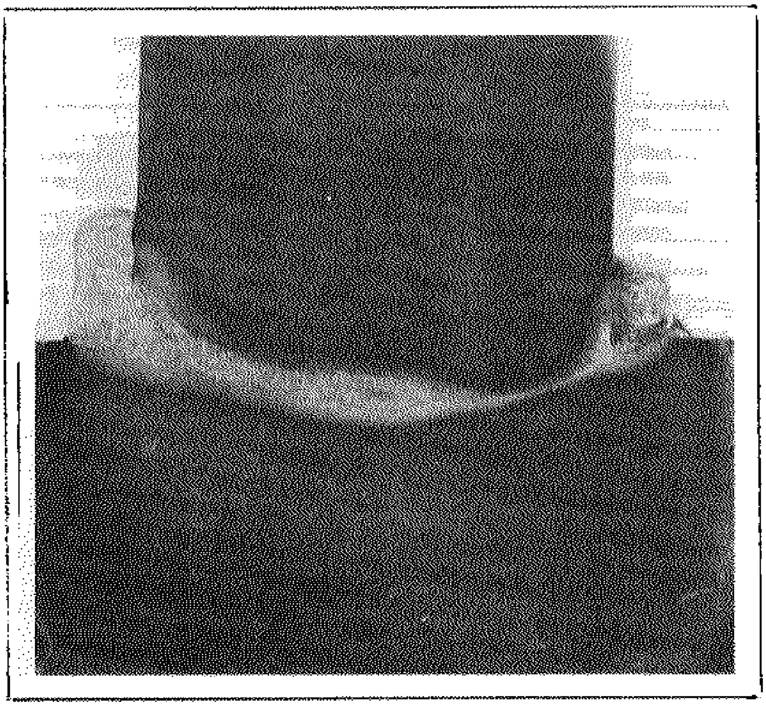


FIGURE 6-11 Cross section of welded stud
Air weld --- Mild steel base plate
(X3.7, 1% nital etch)

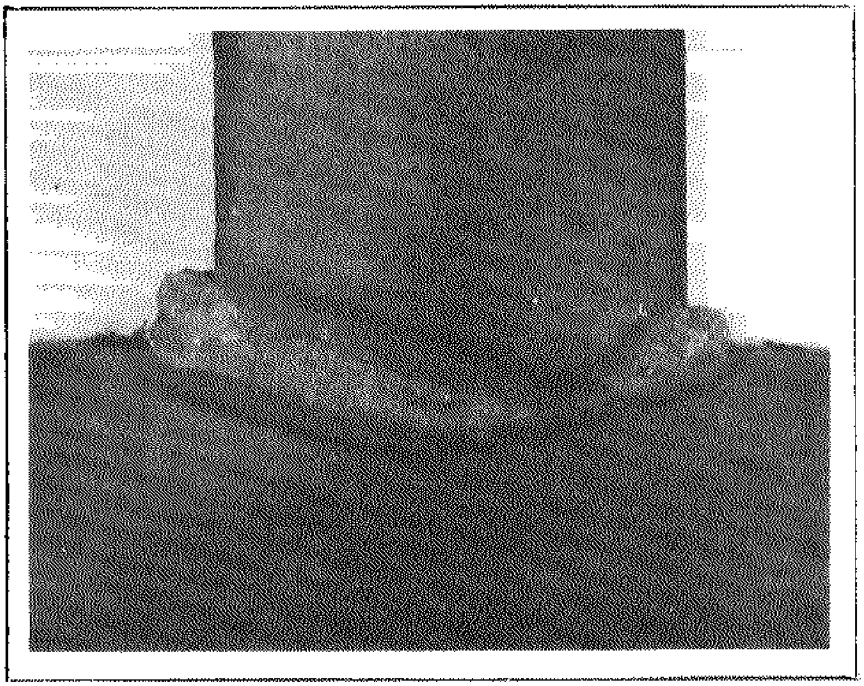


FIGURE 6-12 Cross section of welded stud
Underwater 1/2 in. depth --- Mild steel
base plate (X3.7, 1% nital etch)

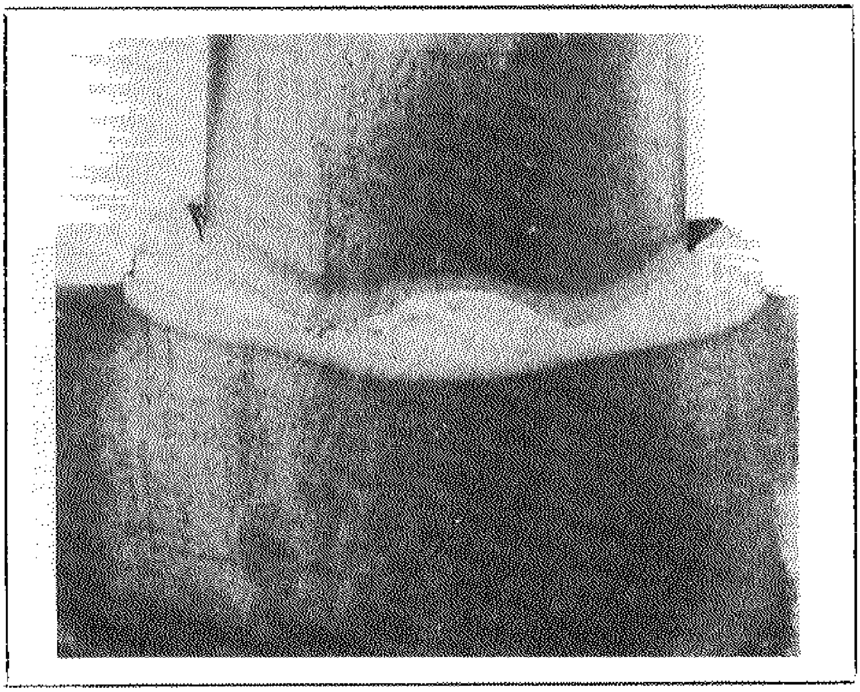


FIGURE 6-13 Cross section of welded stud
Underwater 1 in. depth --- Mild steel
base plate (X3.7, 1% nital etch)

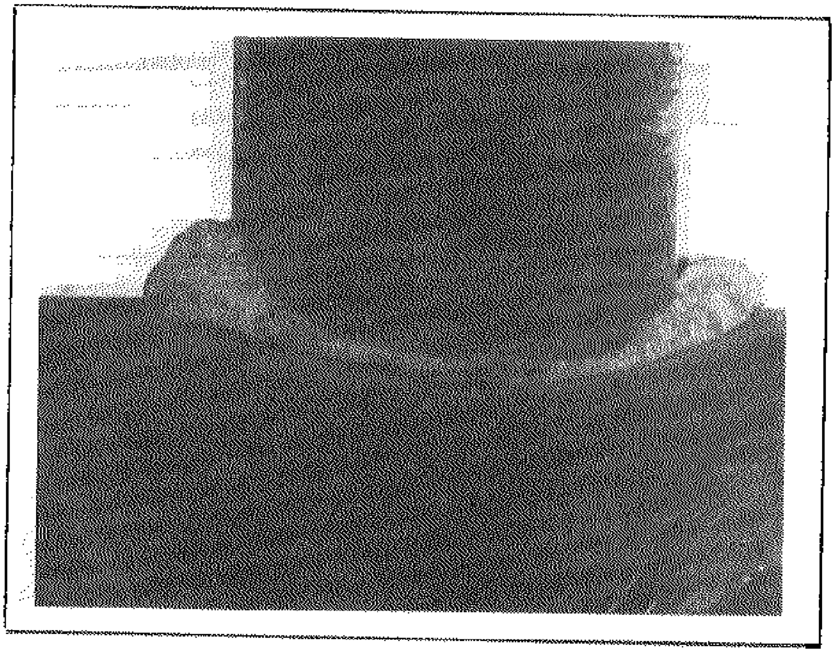


FIGURE 6-14 Cross section of welded stud
Air weld --- HY-80 base plate
(X3.5, 1% nital etch)

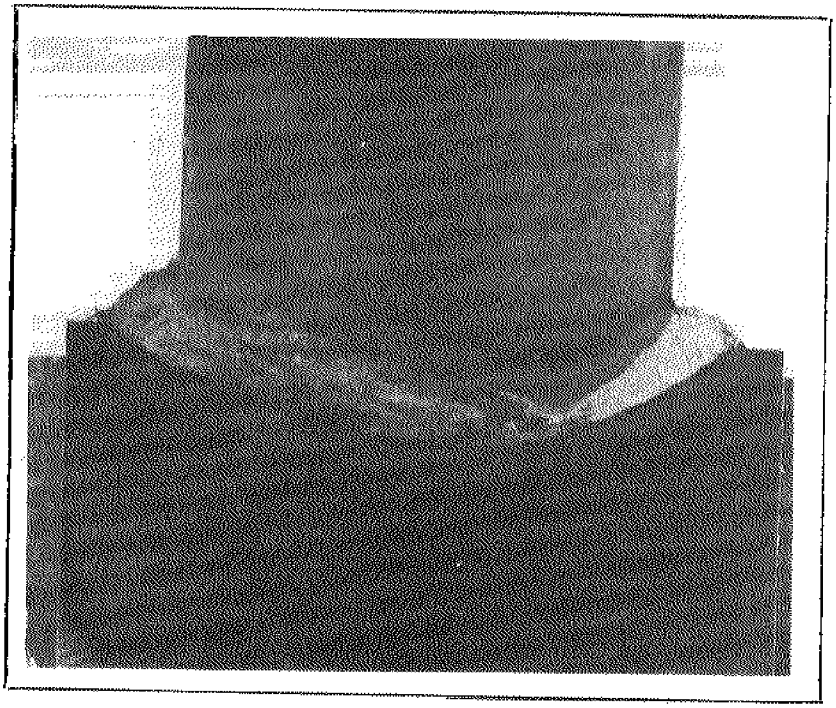


FIGURE 6-15 Cross section of welded stud
Wet surface weld --- HY-80 base plate
(X3.7, 1% nital etch)

The shapes and macrostructures of the weld metal and the heat-affected zone are clearly shown in these photographs. What is interesting is that cross sections of these welds look very similar. This is due to the fact that mechanisms of joining in stud welding are little affected by the presence of water. In case of underwater "wet" arc welding molten metal particles from the electrode must travel in water or in a gaseous environment containing water vapor to the weld metal. In the case of stud welding, on the other hand, most of the water is expelled from the weld region when the stud is attached to the workpiece; therefore, much of the surfaces to be joined are not directly exposed to water. Consequently, the stud welding is inherently suitable for underwater welding. A key to the successful execution of underwater stud welding is to squeeze water out of the weld zone when pressure is

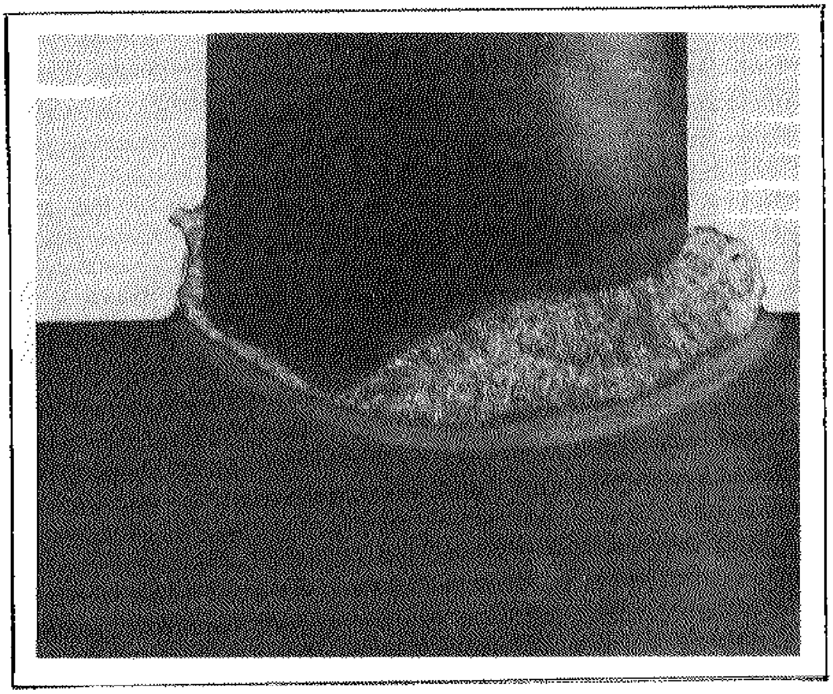
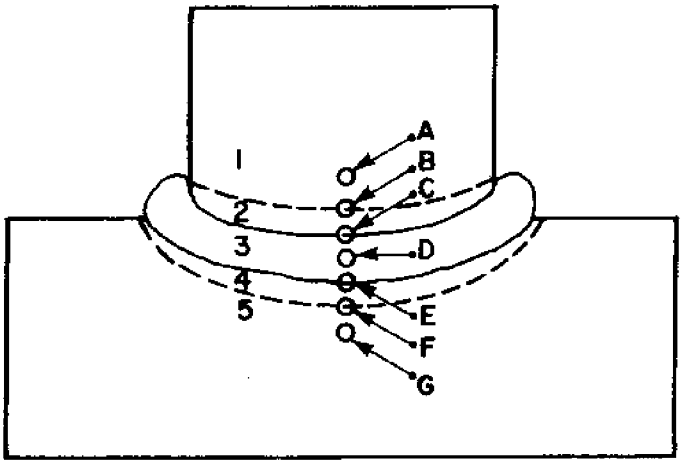


FIGURE 6-16 Cross section of welded stud
Underwater 1 in. depth --- HY-80 base plate
(X3.7, 1% nital etch)

applied to the stud.

(4) Microscopic Examinations. Microscopic examinations were made on some specimens. Figure 6-17 is a schematic illustration of a stud weld section and it shows various areas of the weld zone. The numbering from A to G along the vertical center line of the stud show locations where photographs showing microstructures were taken. The photographs are presented in Chiba's thesis [T12]. Detailed microscopic examinations revealed no cracks in the stud welded specimens made either in air or underwater.



I. STUD
2. HEAT AFFECTED ZONE (STUD SIDE)
3. WELD METAL
4. HEAT AFFECTED ZONE (BASE PLATE SIDE)
5. BASE PLATE

A to G CORRESPOND TO SERIES OF MICROPHOTOGRAPHS

FIGURE 6-17 Stud weld section

(5) Microstructures Tests. After the metallographic examination the specimens were subjected to a microhardness survey to determine their hardness profiles. Figures 6-18 and 6-19 illustrate microhardness distributions for studs welded on low-carbon steel plates. The peak hardness occurred in the border zone of the weld metal and the base metal side of the heat-affected zone (HAZ) in both air and underwater

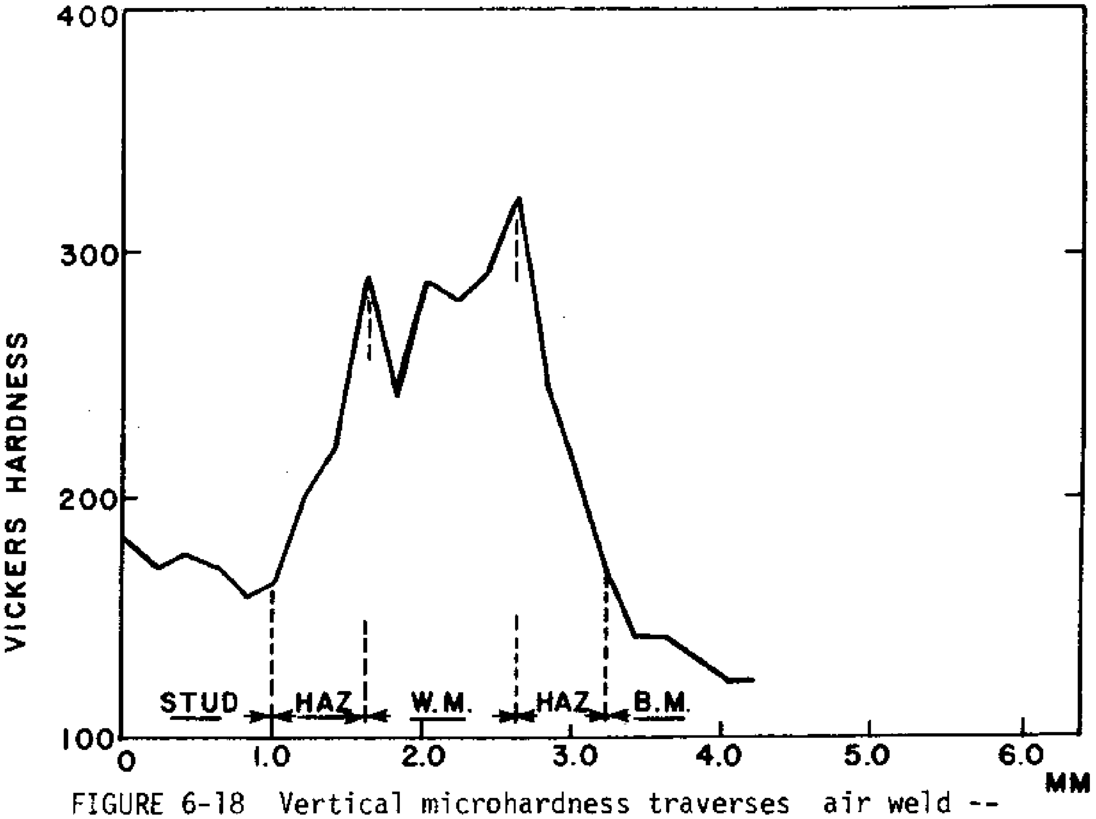


FIGURE 6-18 Vertical microhardness traverses air weld -- mild steel base plate

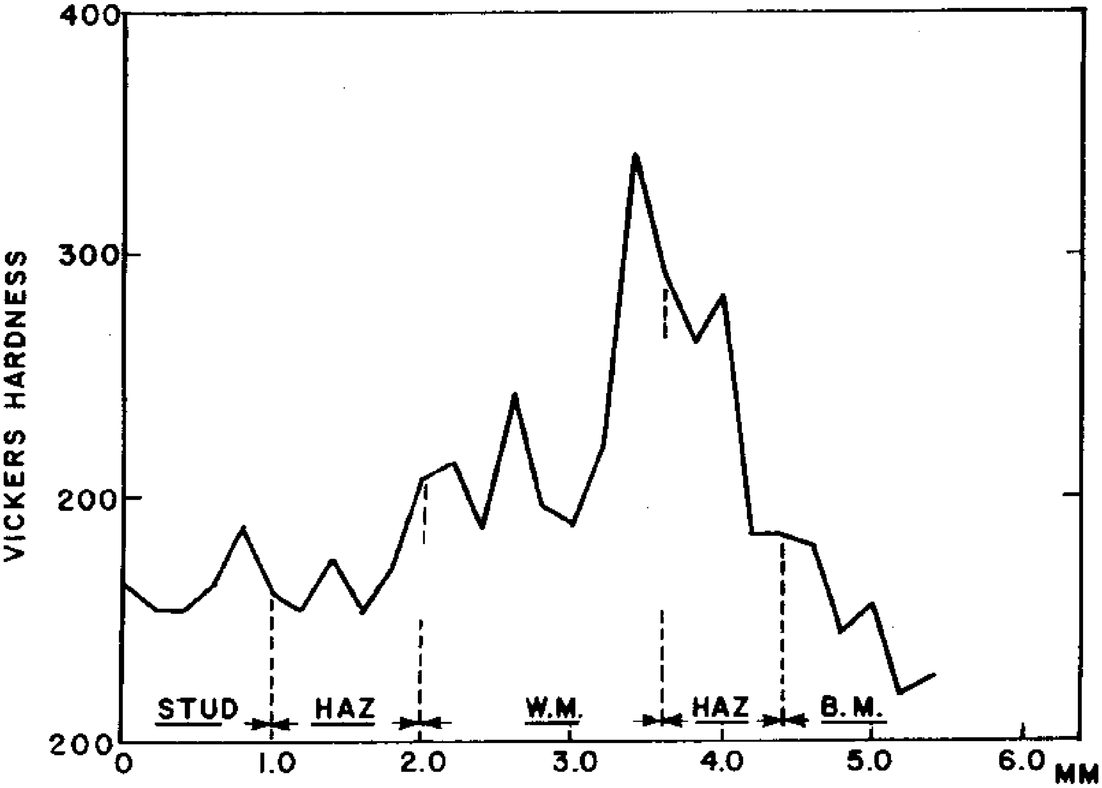


FIGURE 6-19 Vertical microhardness traverses underwater 1/2 in. depth -- mild steel base plate

welds. Figures 6-20, 6-21 and 6-22 show microhardness distributions for studs welded on HY-80 steel plates. The maximum hardness occurred in the base metal size of the HAZ. The second peak appeared in the weld metal adjacent to the stud size of the HAZ. The peak hardness and the shape of the hardness distribution are almost the same in both air and underwater welds on HY-80 steel.

Chiba compared his results on stud welds with results obtained in an earlier study at M.I.T. on shielded metal arc welds, as shown in Figure 6-23 [T12]. The figure shows relationships between the ultimate tensile strength of the base metal and the maximum hardness of the HAZ of welds made in air and underwater. Although hardness values of underwater welds were higher than those of air welds, the difference decreased as the strength level of the material increased. Six data obtained on stud welds were also plotted in Figure 6-20. They were in good agreement with the previous data on shielded metal arc welds.

6.3.3 Advantages of Stud Welding and Its Underwater Applications

Advantages of Stud Welding. Stud welding is a vast improvement over the traditional method of attaching fastener by drilling and tapping a hole into which the stud is screwed. It also competes with, and sometimes replaces, other methods of attaching studs including manual arc welding, resistance welding and brazing. The stud welding process offers many advantages as follows:

(1) All the work is done from one side. Nothing needs to be done on the reverse side.

(2) It eliminates drilling and tapping.

(3) It can attach a stud to a wall too thin to drill or where leakage cannot be tolerated.

(4) It eliminates riverside marking in decorative applications.

(5) It presents a good appearance. There is no need for cleaning or polishing after welding.

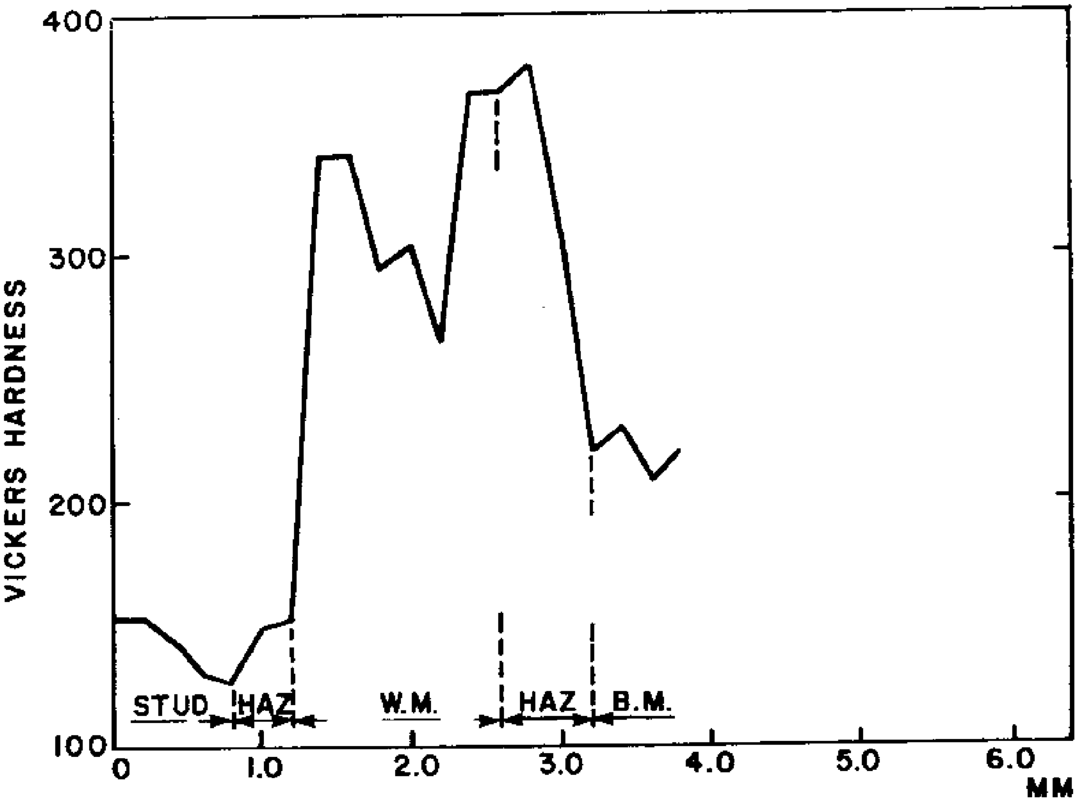


FIGURE 6-20 Vertical microhardness traverses air weld -- HY-80 base plate

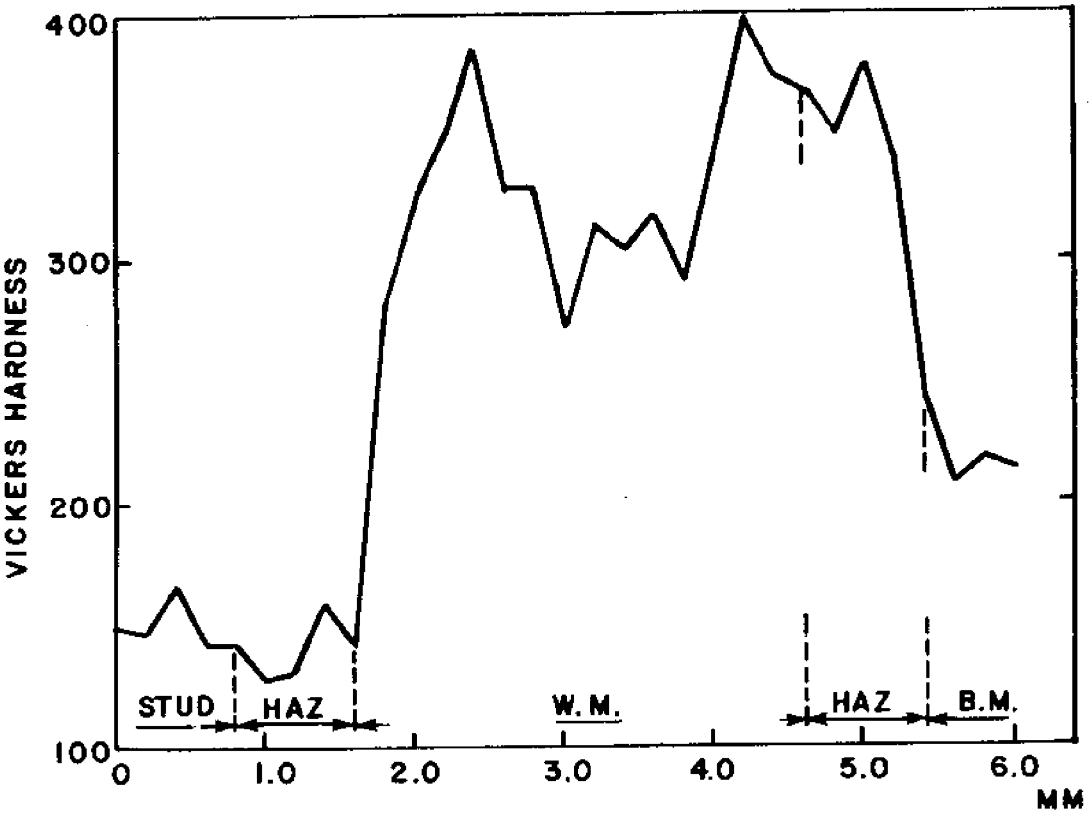


FIGURE 6-21 Vertical microhardness traverses wet surface weld --
HY-80 base plate

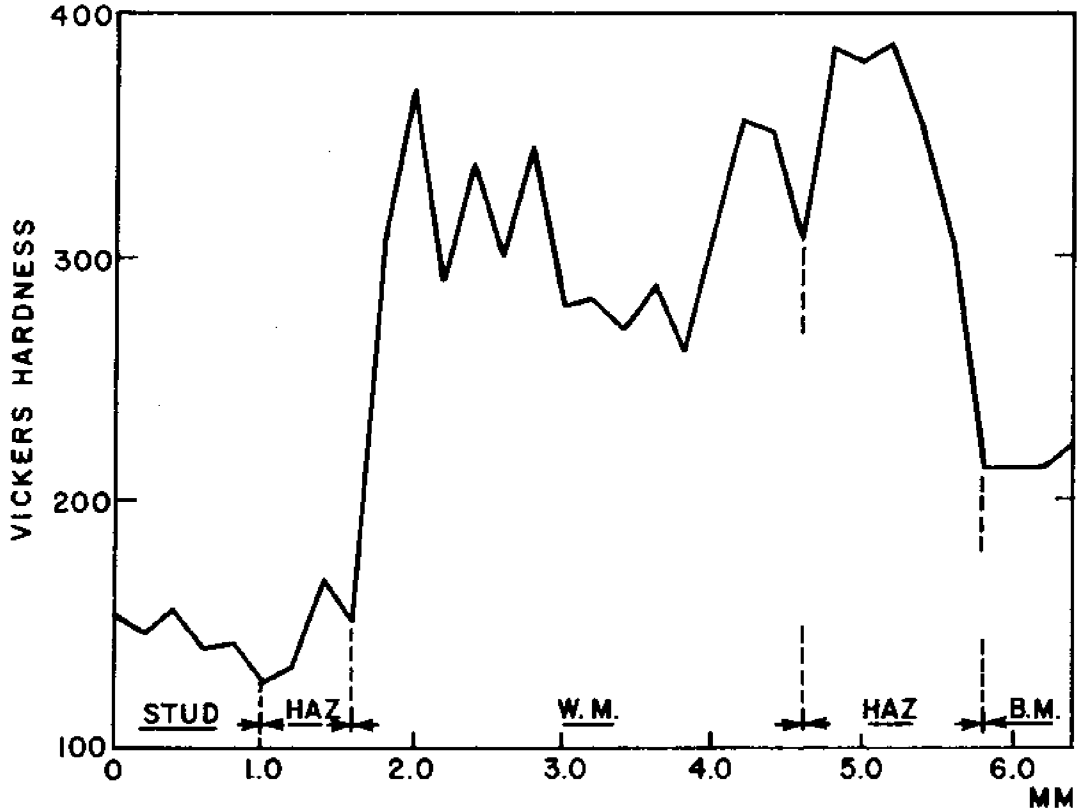


FIGURE 6-22 Vertical microhardness traverses underwater 1 inch depth -- HY-80 base plate

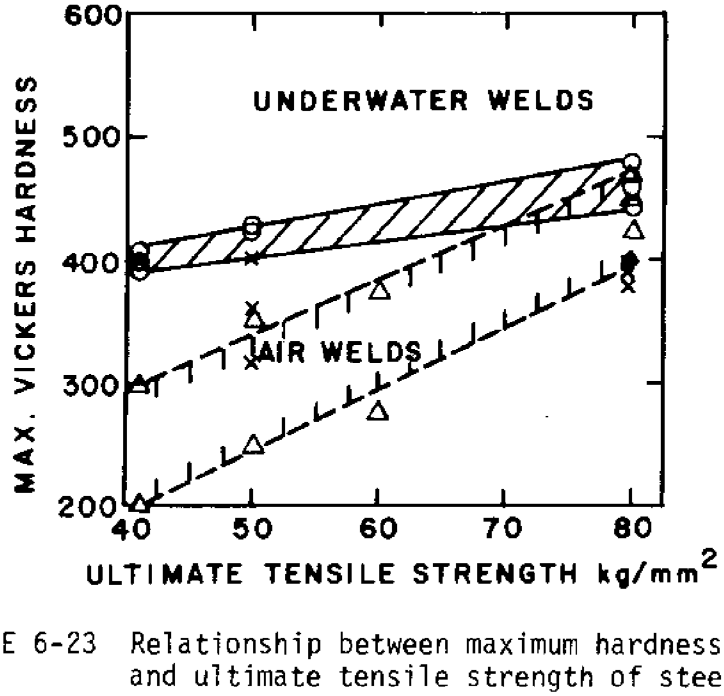


FIGURE 6-23 Relationship between maximum hardness of welds and ultimate tensile strength of steels

(x) --- Maximum hardness from Figures 6-18 through 6-22

(6) It is available in a variety of materials, including low-carbon steel, stainless steel, aluminum, copper alloys, etc.

(7) It has a high production capability. It can be easily automated.

(8) It causes very little distortion.

Some Underwater Applications of Stud Welding. Chiba studied several cases in which underwater stud welding may be applied. He studied the cases of (1) salvaging operations and (2) the burial of a sunken barge.

Figures 6-24 and 6-25 show how underwater stud welding may be used for lifting a sunken object from the bottom of a river or the sea. According to the tensile test results discussed earlier, a 3/4-inch diameter stud can hold a load of at least 10 tons. A 1-inch diameter stud can support a load of 25 tons. It is possible to develop a padeye as shown in Figure 6-25. The operation consists of the following steps:

(1) Attach a number of studs to a sunken object. The studs need to be placed at certain pre-determined locations.

(2) Then attach the padeye with stud holes and tightly secure the padeye to the sunken object by nuts.

(3) Connect the padeye and then lift ship by means of a number of wire ropes.

(4) Lift the sunken object by pulling the ropes.

6.4 Study by Kataoka [T17]

Encouraged by the positive results obtained in an earlier study by Chiba, Kataoka [T17] conducted a further study on underwater stud welding during the 1977/78 academic year. Knowing that underwater stud welding could be made successfully in shallow water, the major objective of the study by Kataoka was to investigate the feasibility of using stud welding in deep sea.

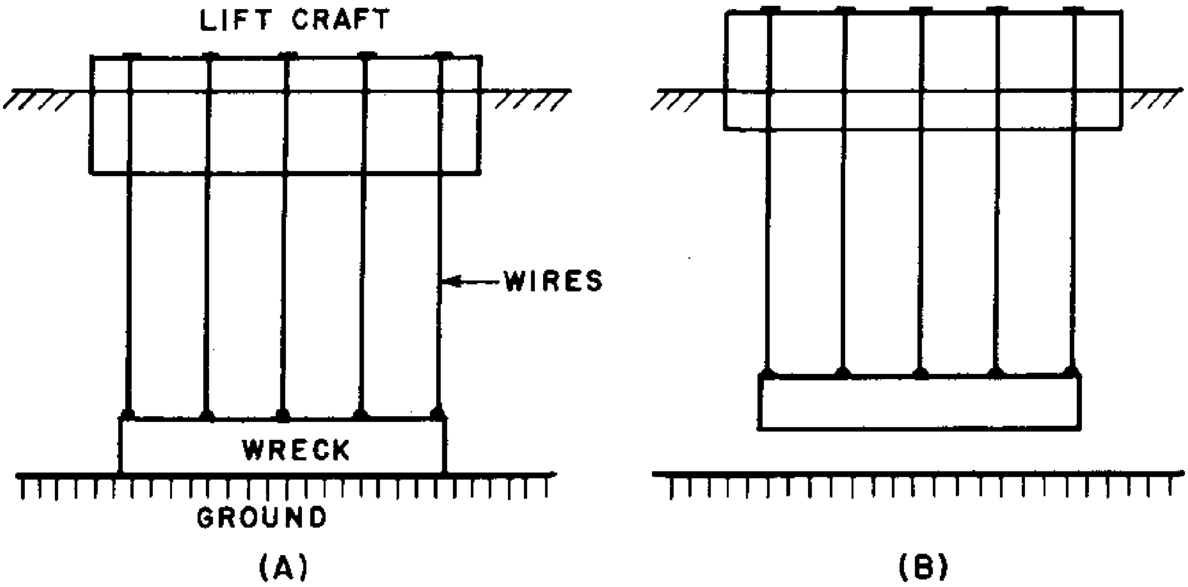


FIGURE 6-24 Lifting operation by lift craft

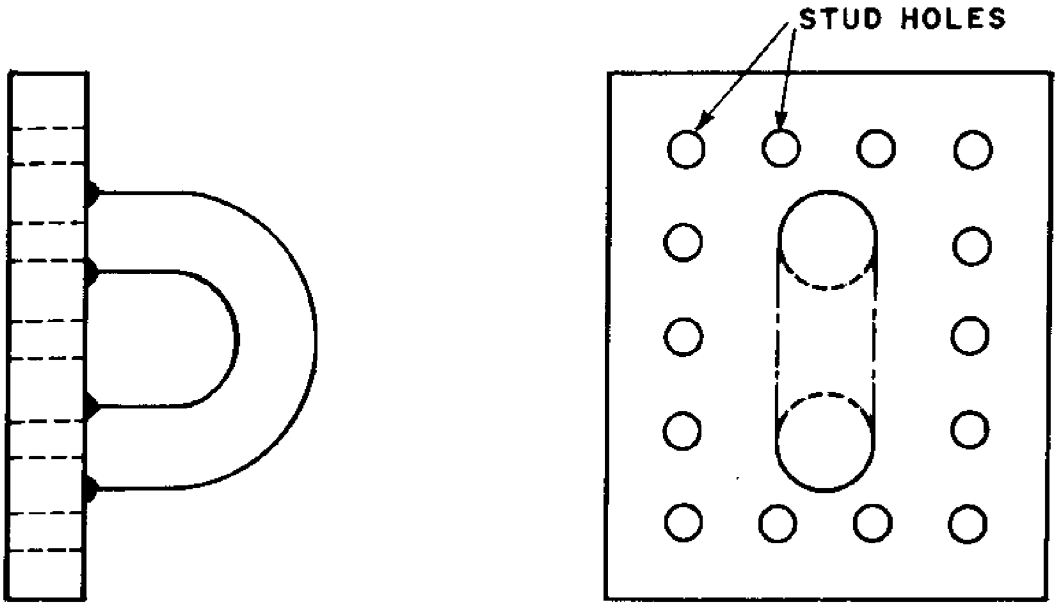


FIGURE 6-25 A padeye for attaching the wreck

To determine the feasibility of using arc stud welding process in deep ocean the effect of water depth on weld quality was investigated using the pressure tank described in Chapter 4. Welds were made at pressures of 0, 25, 50, and 100 psig. After welding tensile tests, metallographic tests, and hardness tests were made of the specimens.

Kataoka also conducted an economic analysis of several diving systems by expanding the analysis by Moore [T7]. The results are presented in Kataoka's thesis.

6.4.1 Experimental Conditions

Experimental conditions used by Kataoka were very similar to those employed by Chiba except in Kataoka's study welds were made in the pressure tank. Figure 6-26 shows the setup of the experiment by Kataoka. A steel specimen was placed in a pan containing water. As no waterproof arc stud welding system was available, only the stud, the base plate, ferrule, and ferrule holder of the stud welding gun were in water. The KSM stud welding gun and the power supply were used.

Since the welding gun had to be placed inside the pressure tank, it was necessary to develop a device which could hold the gun upright during the experiment. If the ferrule slopes to the base plate at an angle, molten metal escapes the ferrule and an undercut occurs. For the purpose of holding the gun upright, a 4-1/2 inch steel pipe, a spring, and a jack were used. As shown in Figure 6-26, the gun was held upright in the pipe which was kept vertically by the jack, and pressed down onto the base plate by the spring. The trigger switch was always turned on with a tape, and a remote switch was attached outside the pressure tank.

Low-carbon steel studs 3/4 inch and 1/2 inch diameter were welded on the low-carbon steel plates 1/2 inch thick. The surface of the base plate was reasonably free of rust, paint, and oil, though some mill scale was on it. Previous study had indicated that little noticeable difference was observed between stud welds made in salt water and those in tap water; therefore, only tap water was used for all experiments.

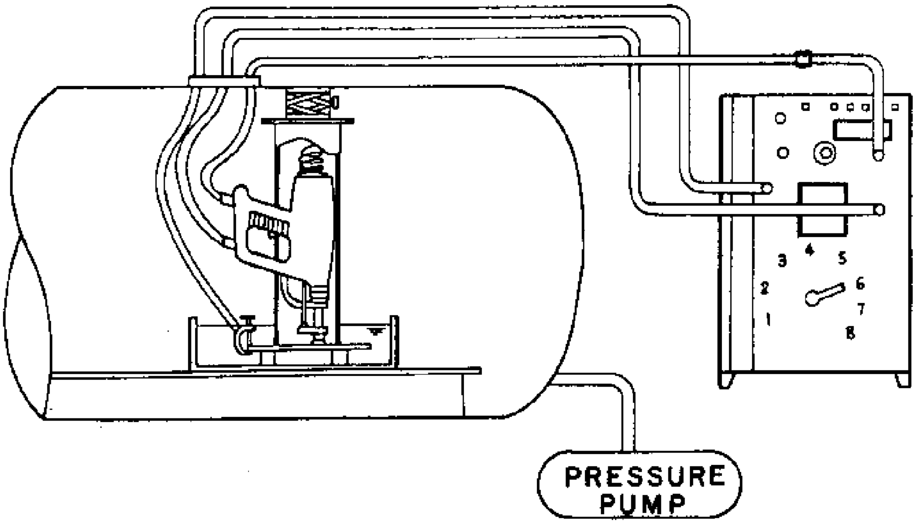


FIGURE 6-26 Under pressure arc stud welding hookup used by Kataoka

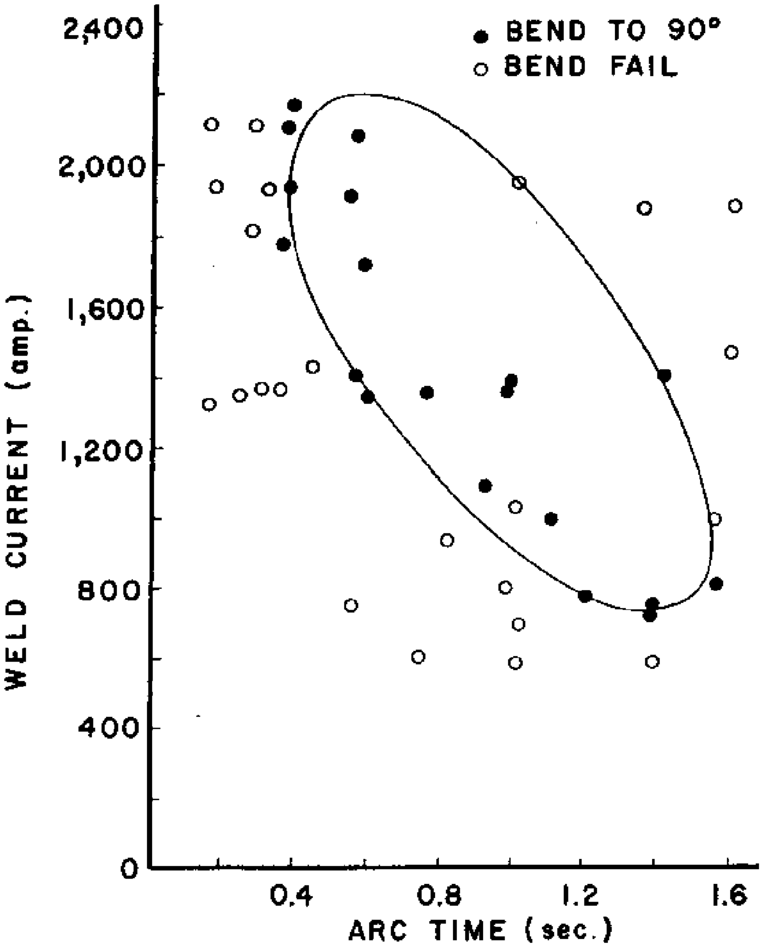


FIGURE 6-27 Arc stud weld quality in air as a function of arc current and time for a 3/4 inch diameter stud [C 38]

6.4.2 Experimental Results

When this study was initiated there had been no published record of stud welding underwater under pressure. We did not even know whether arc stud welding could be successfully made under these conditions. Major purposes of this study were to find out whether stud welding could be made under conditions which simulate deep sea and if so to determine optimum welding conditions.

Figure 6-27 shows the arc stud weld quality in air as a function of arc current and time for a 3/4-inch diameter stud. The data were developed by Baeslack, et al. [C38]. The data were used as a starting point to determine optimum welding conditions underwater and under pressure. In order to simplify ordinary stud welding operations in air the machine has a pre-set arc time and a setting for welding current. For example, we found that an arc current of 1.750 amperes could be obtained at the machine scale of 85. We also found that the matching settings were not accurate. Consequently we decided to measure welding parameters including arc current, arc voltage, and arc time using an oscillograph.

Experimental Results on 3/4-inch Diameter Studs. First, an attempt was made to determine optimum conditions for welding a 3/4-inch diameter stud to a low-carbon steel plate. Figure 6-28 shows how weld quality changed when arc time and arc length changed in one inch deep water. As the best weld quality was obtained when the arc length was 0.13 inch and the pre-set arc time dial was 85, the arc length was fixed at 0.13 inch to reduce a variable for the experiments with 3/4-inch diameter studs.

Figure 6-32 shows the underwater weld quality as a function of arc time and arc current, although the weld quality was determined by investigating only the outside appearance of the weld metal. The real arc time was measured with an oscillograph, instead of the pre-set arc time dial, because the real arc time changes when arc current changes at the same pre-set arc time dial setting. The arc length was 0.13 inch. It was found by comparing Figures 6-27 and 6-29 that the combinations of

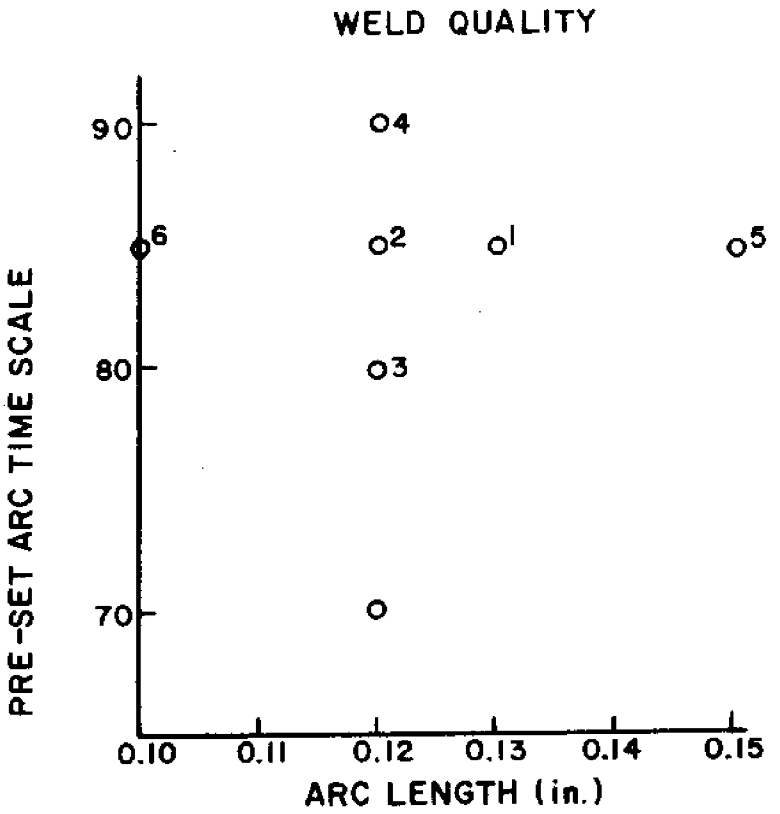


FIGURE 6-28 Underwater arc stud weld quality as a function of arc length and time for a 3/4 in. diameter stud at 0 psi

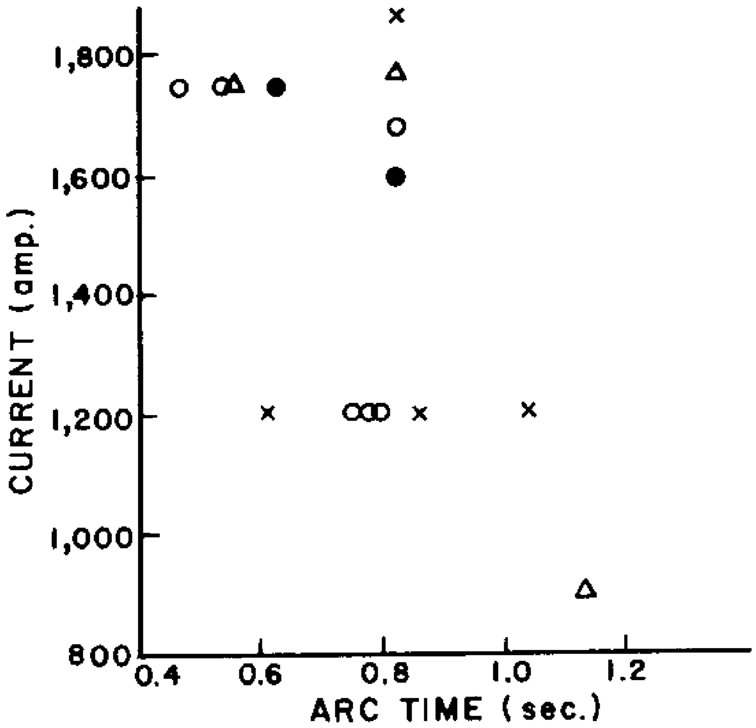


FIGURE 6-29 Underwater arc stud weld quality as a function of arc time and current for a 3/4 in. diameter stud at 0 psi

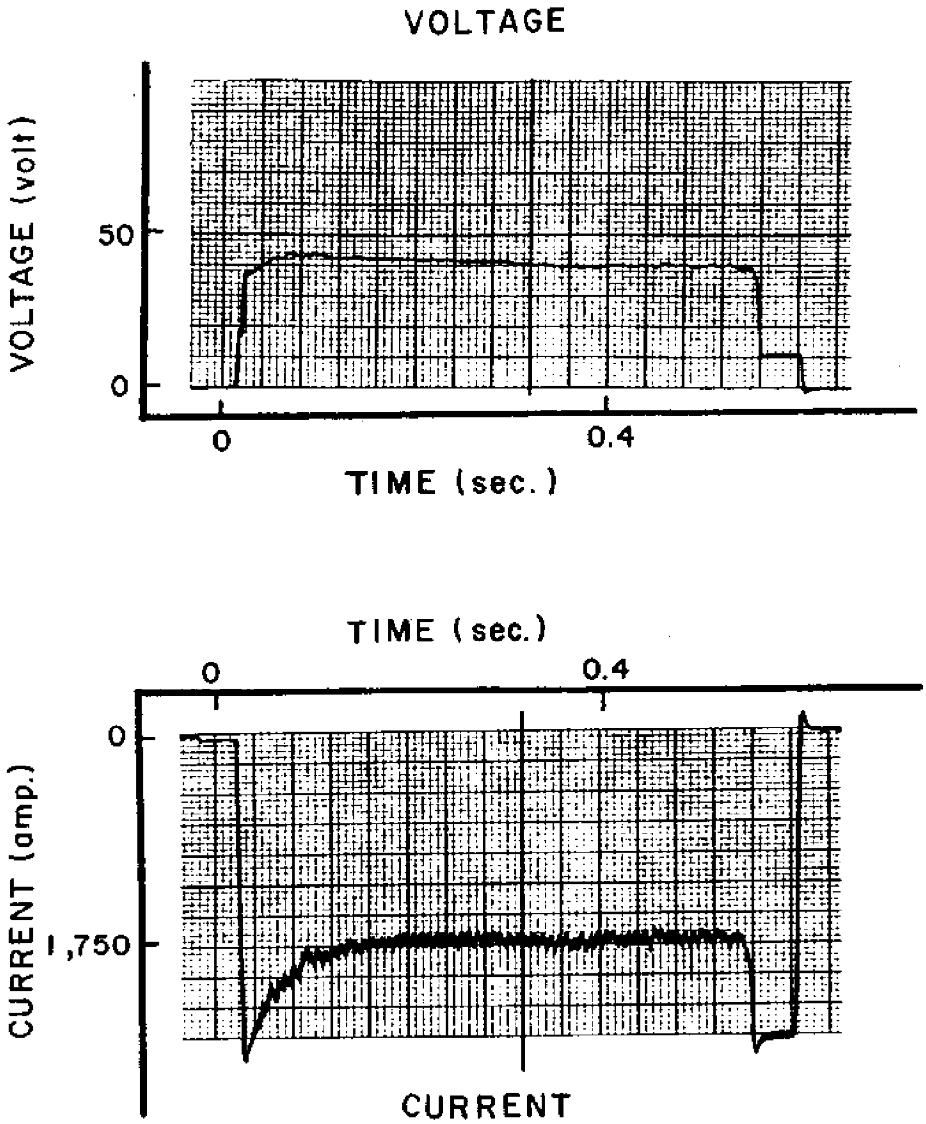


FIGURE 6-30 Oscillographic trace of arc stud welding voltage and current for 3/4 in. diameter stud (0 psi in air)

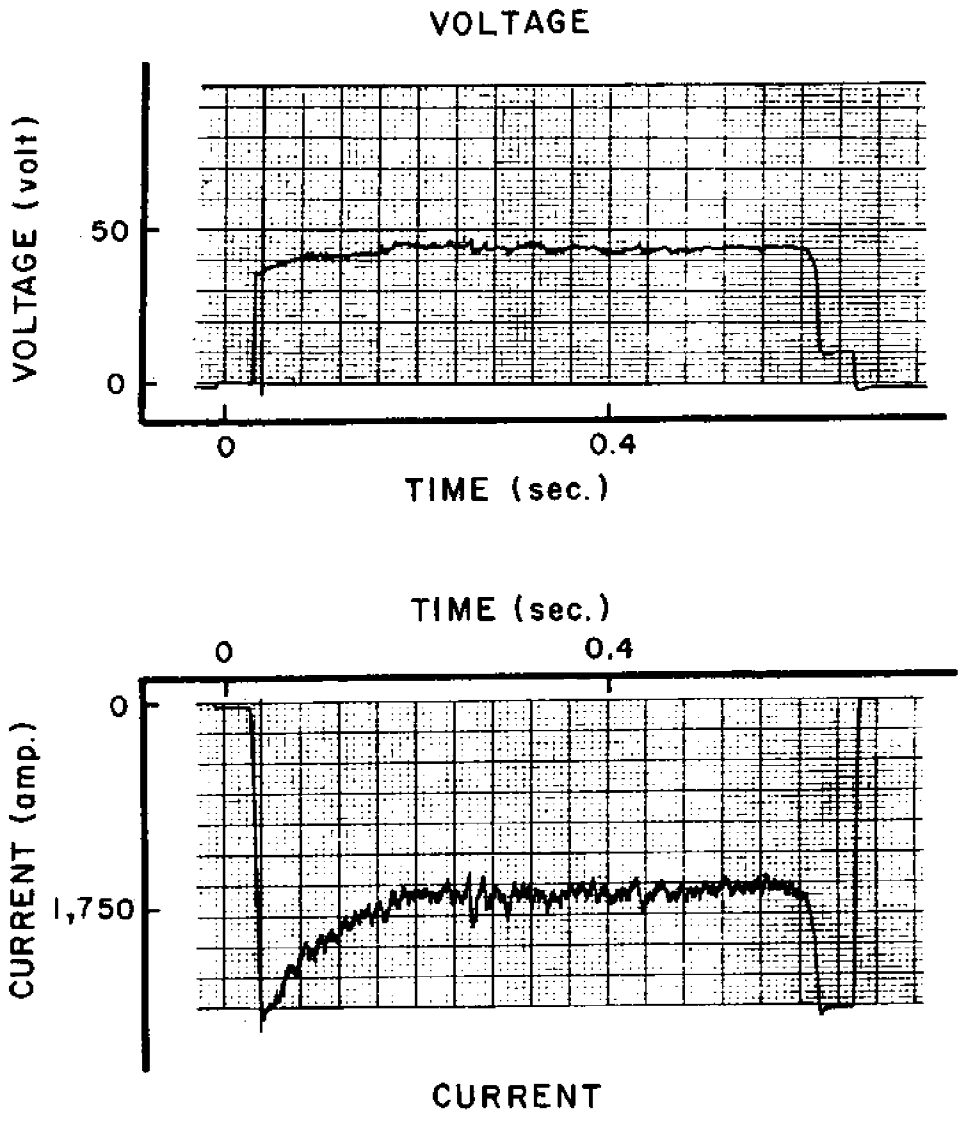


FIGURE 6-31 Oscillographic trace of arc stud welding voltage and current for 3/4 in. diameter stud (0 psi underwater)

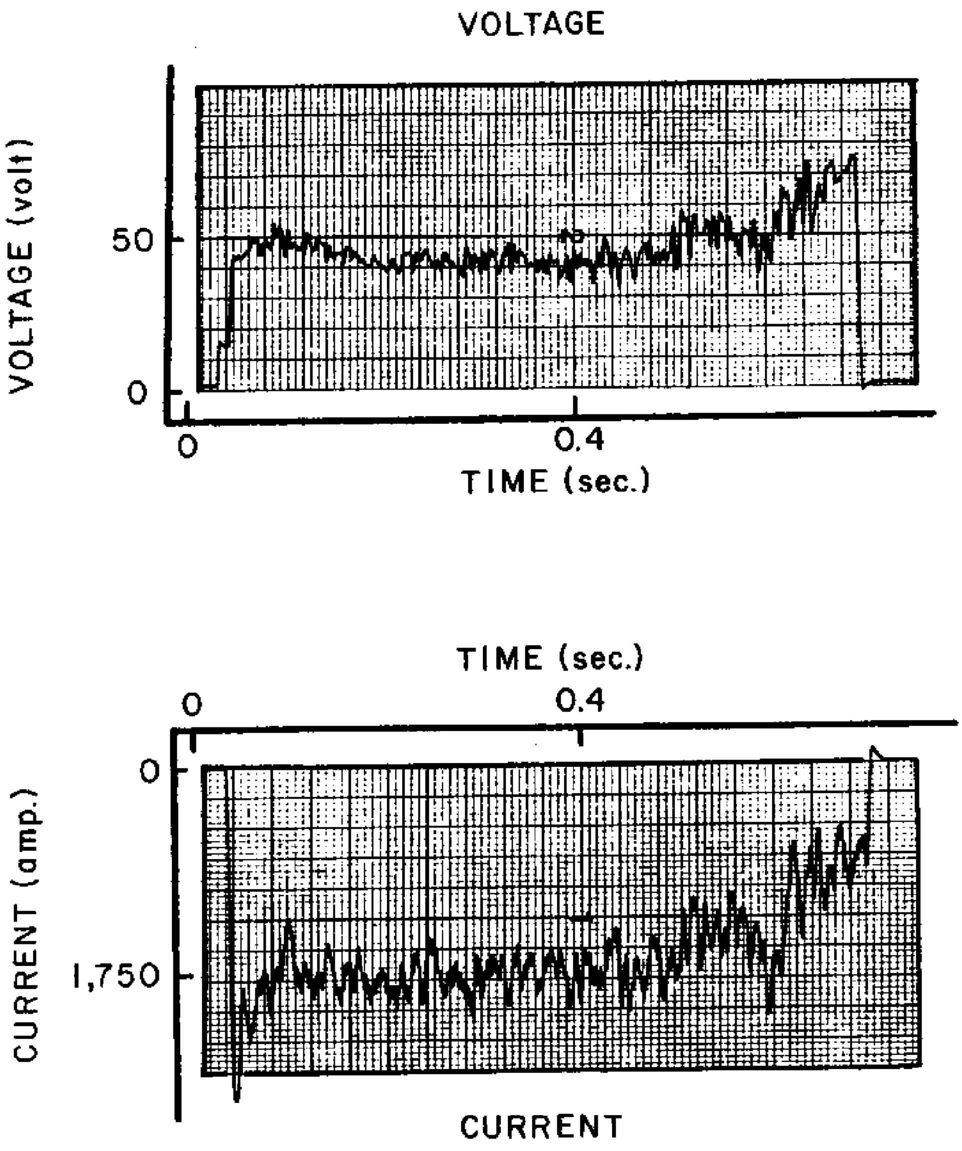


FIGURE 6-32 Oscillographic trace of arc stud welding voltage and current for 3/4 inch diameter stud (25 psi in air)

welding current and arc time which result in the production of a satisfactory weld underwater is less flexible than in air. Although the stud weld made underwater had some porosity, the quality of the weld was reasonably good. This is verified by Figures 6-30 and 6-31, oscillographic traces of the arc voltage and welding current at 0 psig in air and water, respectively. The presence of water caused little disturbance on arc characteristics.

Chiba [T12] reported that the welding arc did not initiate at all without using steel wool as an arc initiator. In the experiment conducted by Kataoka, however, the arc initiated almost always without using steel wool. Kataoka concluded that the problem experienced by Chiba was probably caused by a poor ground or poor connections.

Kataoka encountered troubles when he started welding under pressure. Experiments were performed in air under pressures of 25 and 50 psig, and in water under pressures of 50 and 100 psig. The arc was bent by the pressure, and the higher the pressure, the greater the bending. In water, the arc was less affected than in air, but it was still significantly bent at 100 psig. Figures 6-32 through 6-35 show oscillographic traces of the welding voltage and current of arc stud welds made in air and underwater with the presence of pressure. The arc stability was seriously disturbed by pressure, especially when welds were made in air. Qualities of welds were very poor.

Experimental Results on 1/2-inch Diameter Studs. Kataoka decided to conduct experiments using studs 1/2-inch in diameter. Table 6-2 shows the quality of arc stud welds in air using 1/2-inch diameter studs when arc length, arc time, and arc current changed. The weld quality was determined by examining the appearance of the welds only. It was decided from these results to use an arc length of 0.09 inch, a power of 6 (about 900 amperes), and pre-set arc time dial setting 63 to 75.

To investigate the effect of pressure on the weld quality, experiments with the same conditions were done under pressures of 0, 25, 50, and 100 psig in air and underwater. The results are summarized in Table 6-3.

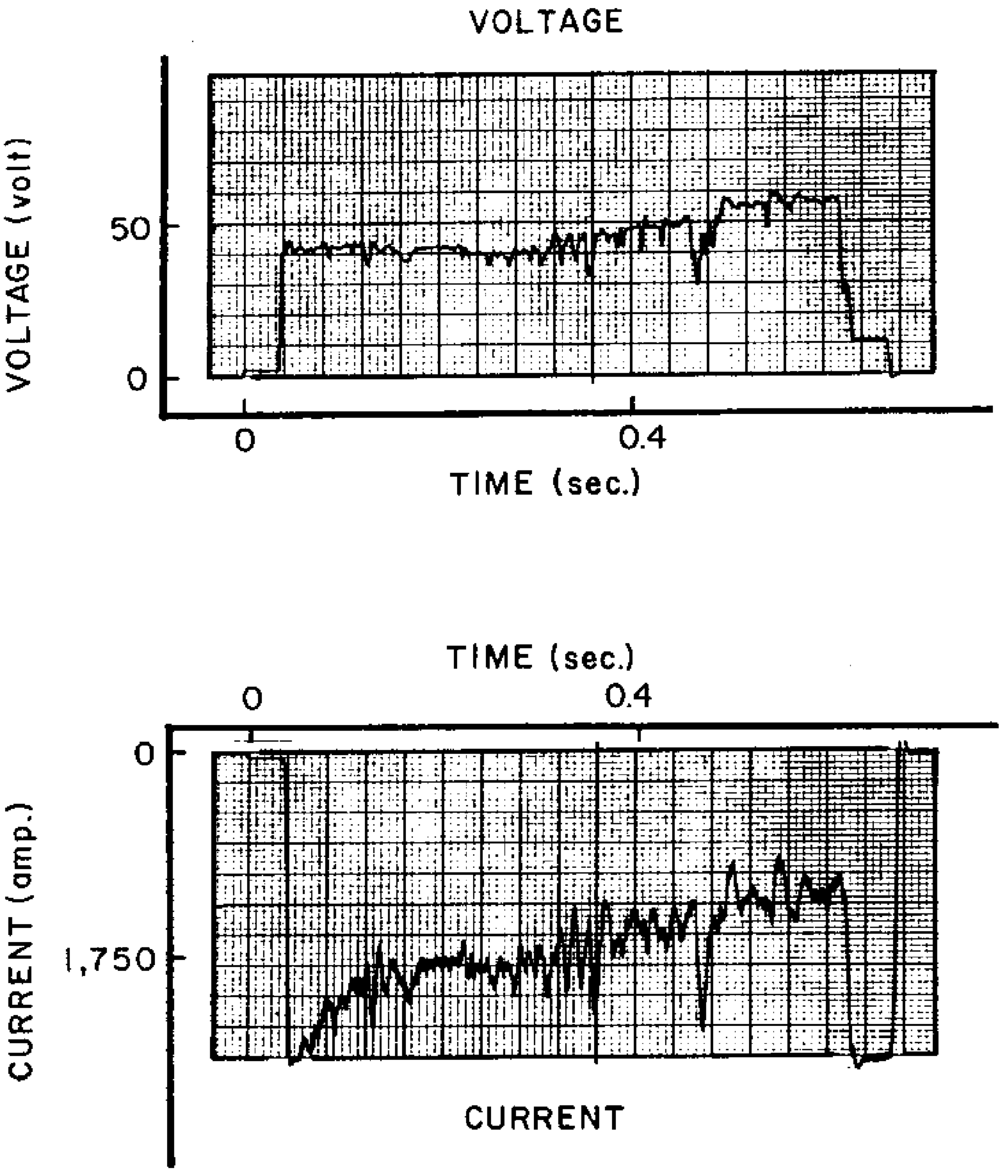


FIGURE 6-33 Oscillographic trace of arc stud welding voltage and current for 3/4 in. diameter stud (50 psi in air)

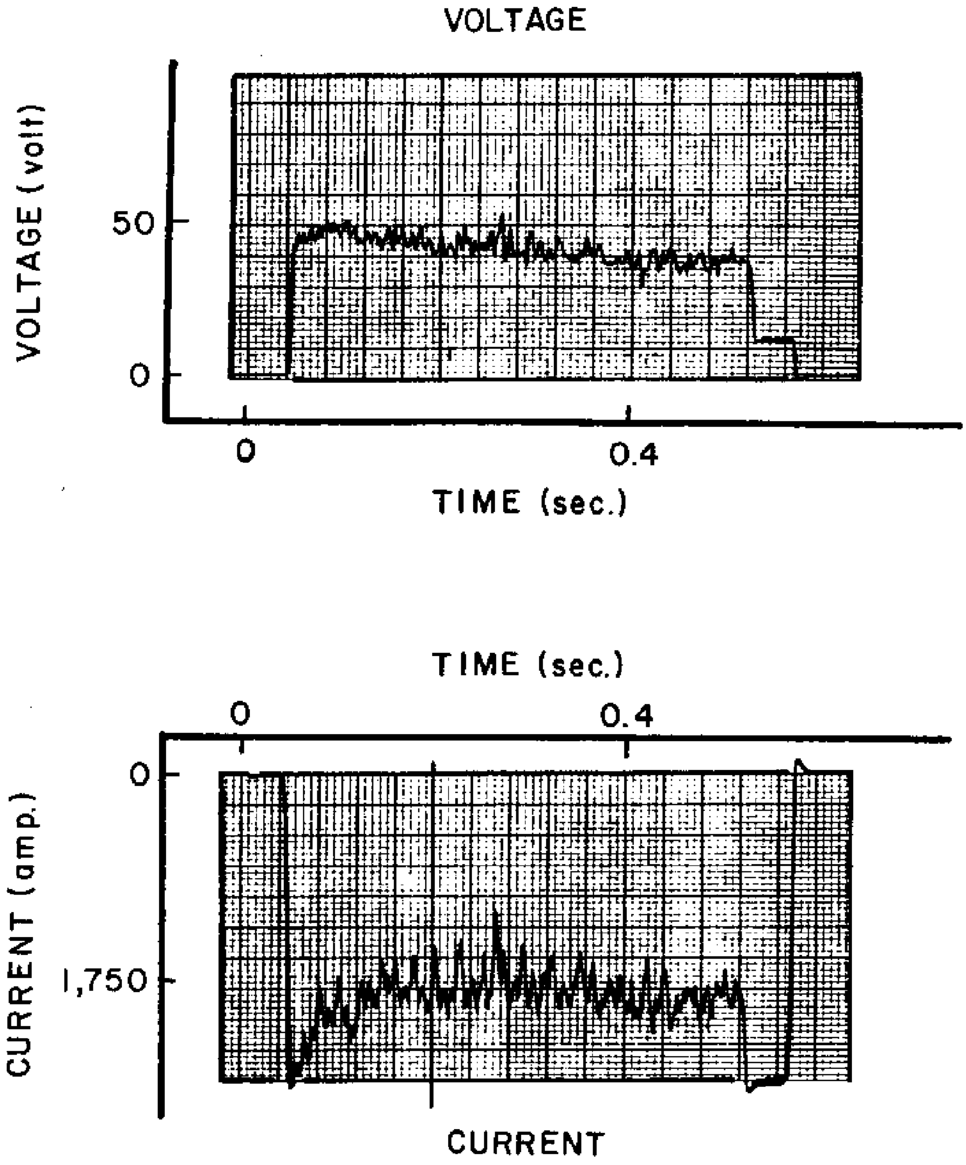


FIGURE 6-34 Oscillographic trace of arc stud welding voltage and current for 3/4 in. diameter stud (50 psi underwater)

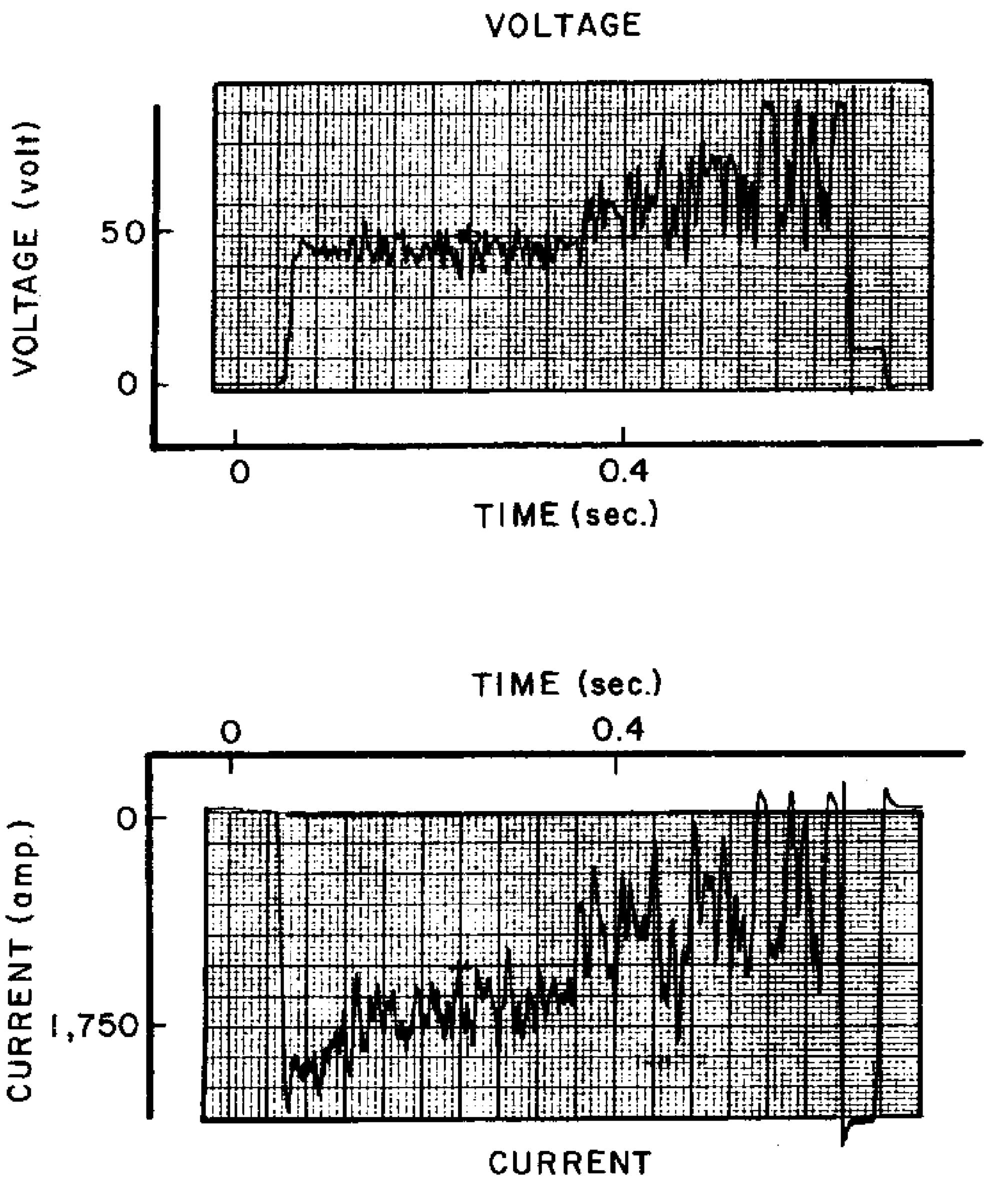


FIGURE 6-35 Oscillographic trace of arc stud welding voltage and current for 3/4 in. diameter stud (100 psi underwater)

Table 6-2 UNDERWATER ARC STUD WELD QUALITY AS A FUNCTION OF ARC LENGTH, CURRENT, AND TIME FOR 1/2 In. DIAMETER STUDS

Pressure	Arc Length	Power	Pre-set Arc Time Scale	Weld Quality
0 psi	0.15 in.	7	65	undercut
0 psi	0.09 in.	7	65	undercut
0 psi	0.06 in.	6	65	good
0 psi	0.06 in.	6	70	good
0 psi	0.06 in.	6	55	lack of fusion
0 psi	0.09 in.	6	70	undercut
0 psi	0.09 in.	6	75	undercut
0 psi	0.09 in.	6	67	not enough fillet
0 psi	0.09 in.	6	65	better
0 psi	0.09 in.	6	63	better

Table 6-3 WELDING CONDITION FOR 1/2 In. DIAMETER STUDS

Specimen No.	Pressure	Environment	Arc Length	Power	Pre-set Arc Time Scale	Real Arc Time	Weld Quality
1	0 psi	air	0.09 in.	6	65	0.452 sec.	good with some slag inclusion
2	25 psi	air	0.09 in.	6	65	0.384 sec.	good weld with some lack of fusion
3	50 psi	air	0.09 in.	6	65	0.392 sec.	good weld with some lack of fusion
4	100 psi	air	0.09 in.	6	65	0.384 sec.	lack of fusion
5	25 psi	air	0.09 in.	6	75	0.628 sec.	good
6	50 psi	air	0.09 in.	6	75	0.624 sec.	good
7	100 psi	air	0.09 in.	6	75	0.636 sec.	good
11	0 psi	water	0.09 in.	6	63	0.464 sec.	good
12*	0 psi	water	0.09 in.	6	63	0.484 sec.	good
13*	25 psi	water	0.09 in.	6	66	0.495 sec.	good
14*	50 psi	water	0.09 in.	6	63	0.444 sec.	good
15*	100 psi	water	0.09 in.	6	66	0.520 sec.	porosity

* welded with steel wool

After making several welds using various combinations of welding parameters the investigators were able to produce good welds underwater under pressure. Table 6-3 presents short descriptions of the quality of the welds. Detailed discussions of the test welds are given in Kataoka's thesis. The experimental results can be summarized as follows:

(1) It was possible to obtain good welds in air up to 100 psig.

(2) It was possible to obtain good welds underwater under pressure up to 50 psig. However, the investigators were not able to produce a good weld underwater under 100 psig within the period of research available to them.

(3) It was found that arc initiation was difficult when welds were made underwater under pressure. Therefore, steel wool arc initiator was used for underwater welds made under pressure.

Figures 6-36 and 6-37 show underwater stud welds made under 25 psig and 50 psi, respectively after bend testing. The figures show that welds with good quality could be achieved underwater up to 50 psi pressure. Figure 6-38 shows the appearance of the bend test result of Specimen #15 made underwater under 100 psi. Figures 6-39 through 6-41 show oscillographic traces of arc voltage and arc current of underwater stud welds made 25, 50, and 100 psi. The arc voltage and current were reasonably stable with welds made under 25 and 50 psi; however, arc characteristics were less stable with welds made under 100 psi.

Microscopic examination was performed on each specimen and a number of photographs were taken to show microstructures. Their results are presented in Kataoka's thesis. The specimens were also subjected to a hardness survey to determine their hardness profiles. Measured were the hardness at the stud, the heat affected zone in the stud, the weld metal, the heat-affected zone in the base metal, and the base metal. Table 6-4 shows hardness test results which were measured with a Rockwell hardness tester 15-N and converted to Vicker's diamond pyramid hardness

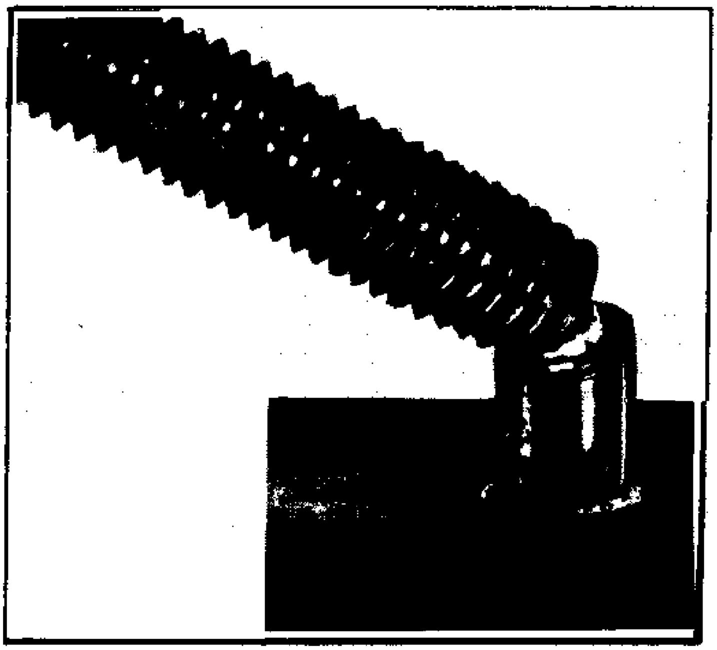


FIGURE 6-36 Appearance of bend test result
(25 psi underwater)
Specimen No. 13

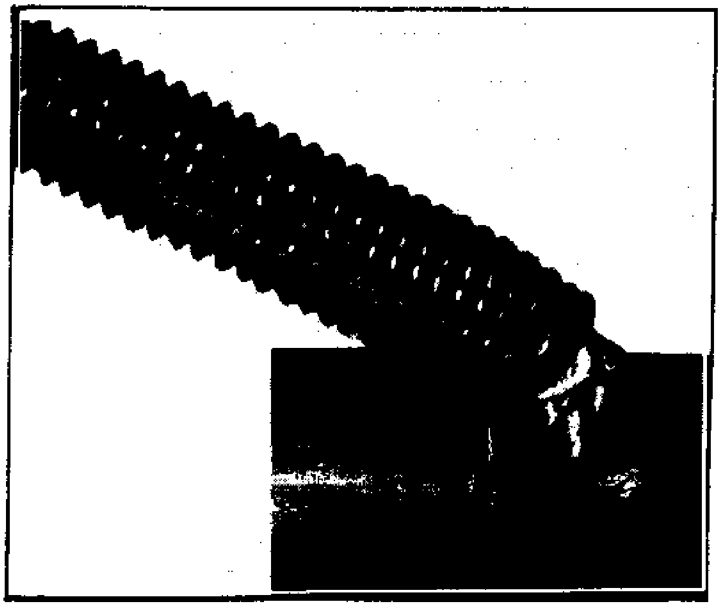


FIGURE 6-37 Appearance of bend test result
(50 psi underwater)
Specimen No. 14

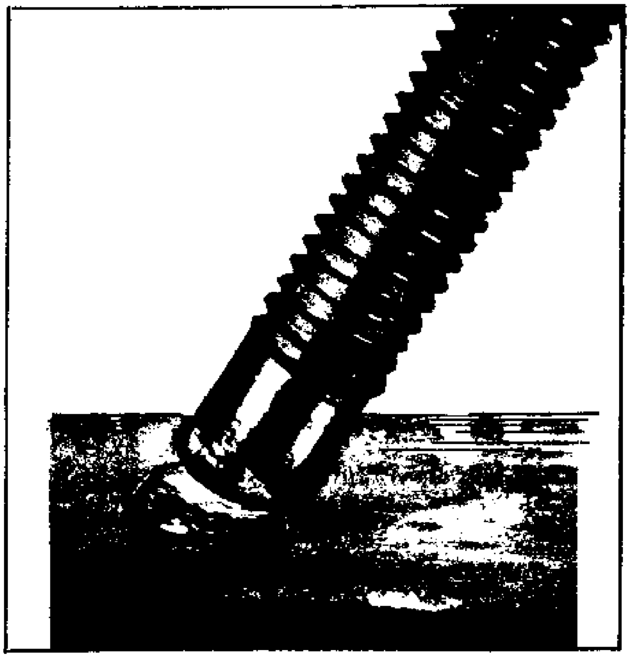


FIGURE 6-38 Appearance of bend test result
(100 psi underwater)
Specimen No. 15

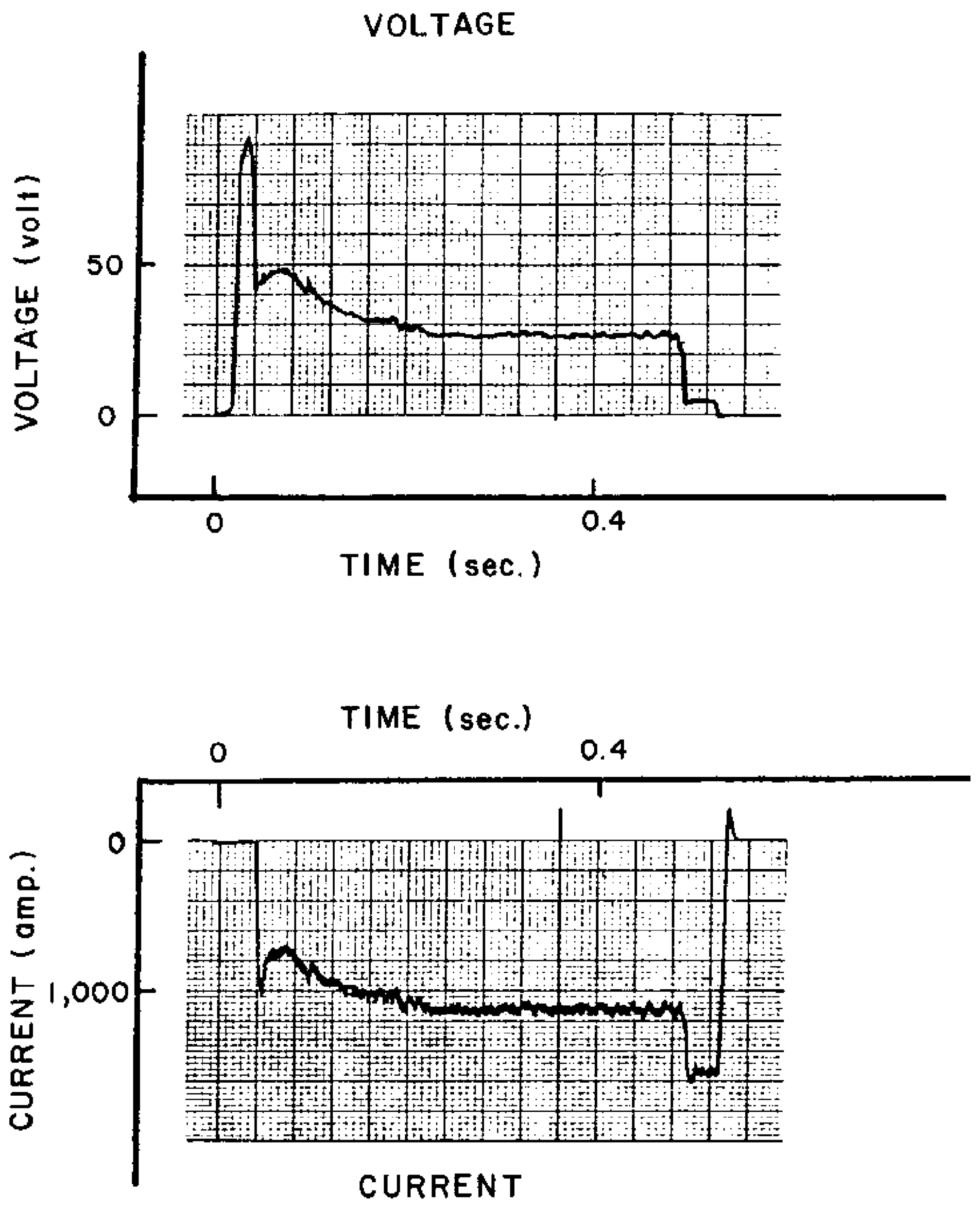


FIGURE 6-39 Oscillographic trace of arc stud welding voltage and current for 1/2 in. diameter stud (25 psi underwater, with steel wool)

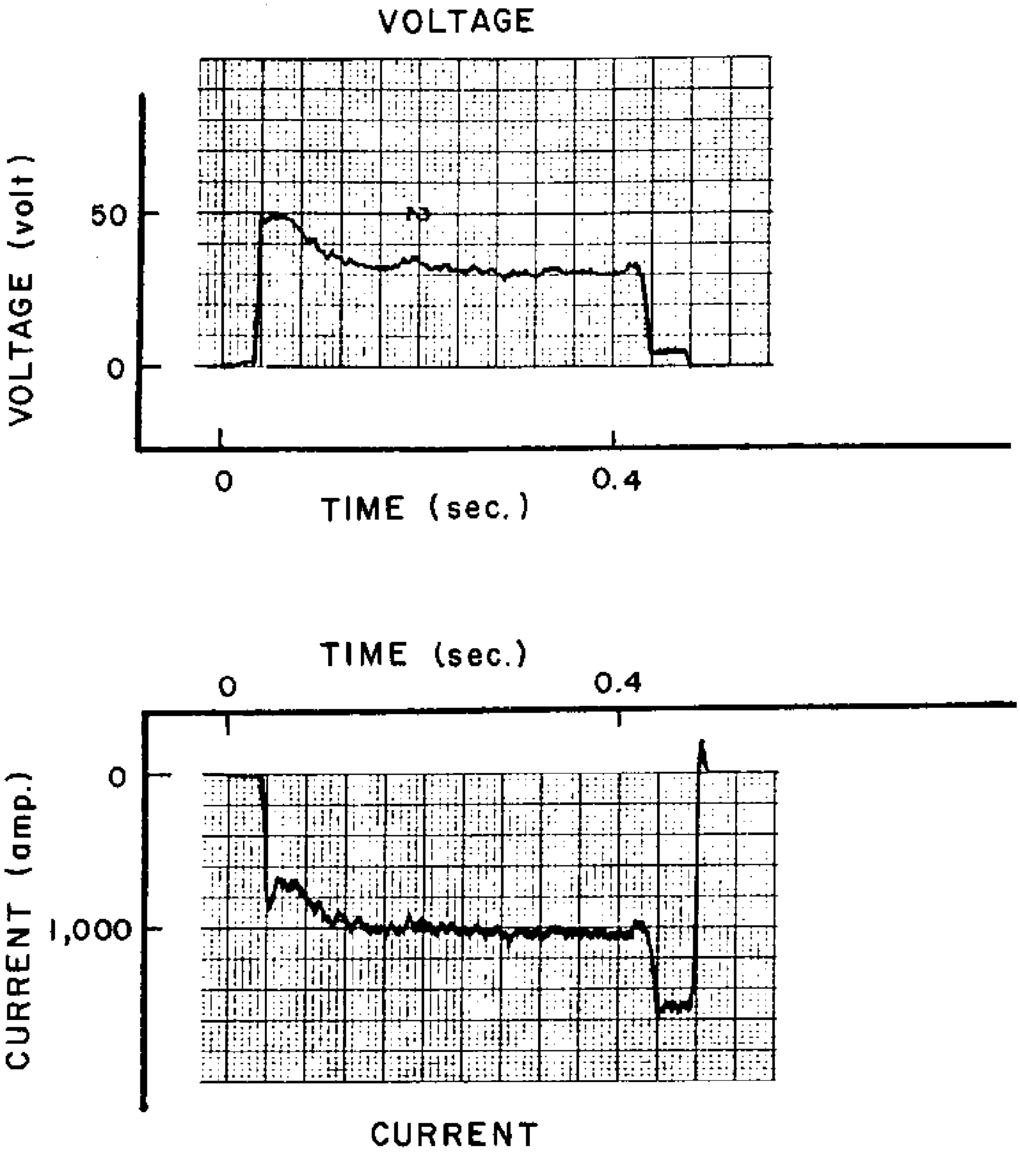


FIGURE 6-40 Oscillographic trace of arc stud welding voltage and current for 1/2 in. diameter stud (50 psi underwater, with steel wool)

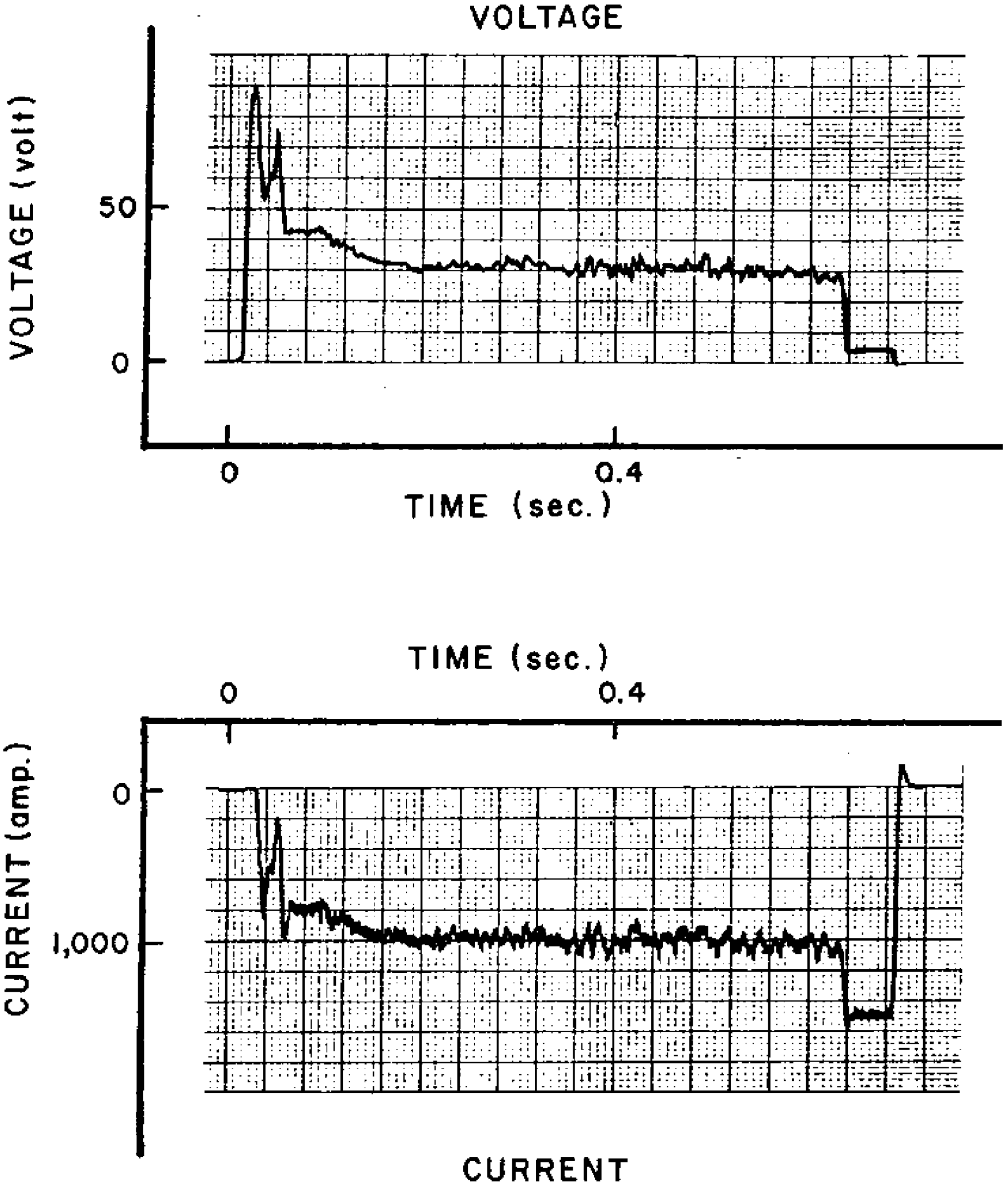


FIGURE 6-41 Oscillographic trace of arc stud welding voltage and current for 1/2 in. diameter stud (100 psi underwater, with steel wool)

Table 6-4 HARDNESS TEST RESULTS

Specimen No.	Stud		HAZ		Weld metal		HAZ		Base metal	
	R	V	R	V	R	V	R	V	R	V
1	62.5	153	59.3	115	66.0	194	62.8	157	58.5	105
2	61.0	135	60.1	124	73.1	279	66.3	198	56.3	80
3	61.8	145	59.2	113	74.0	285	65.0	182	55.4	69
4	62.3	149	60.0	123	74.9	299	67.1	206	54.8	63
5	64.8	180	60.9	134	72.2	267	69.7	238	55.5	70
6	62.2	148	60.0	123	70.1	242	65.0	182	55.3	68
7	62.0	147	58.3	103	70.6	247	65.2	185	55.2	67
11	61.5	141	61.5	141	73.0	275	66.7	202	57.5	93
12	64.5	177	63.0	158	75.6	311	73.3	277	56.0	76
13	62.5	153	64.5	177	76.8	329	71.3	255	59.5	117
14	64.0	170	62.5	153	70.8	249	66.0	194	55.5	70
15	63.0	158	64.8	180	72.0	264	65.0	182	53.0	40

R Rockwell 15-N Hardness

V Vickers Hardness (10 kg)

(10kg). The table exhibits the average of hardness which was measured at least on three locations in every region. The high hardness was in the weld metal in all specimens.

6.4.3 Initial Design of a Prototype Tool

An effort was made to develop an initial design of a prototype tool using stud welding for deep-sea applications. Figure 6-42 shows a conceptual design of an integrated underwater stud welding unit. The unit has four stud heads and can attach four studs to the work piece in a consecutive order within two seconds. If 3/4-inch diameter studs are used, for example, each stud can hold a load of 8 tons thus a 32-ton capacity can be achieved with the four-stud unit. In welding operation, stud welding unit can be held in position by electrical magnets. The unit is energized by pressing a button either by a diver on site or by remove control switches. New studs can be fed automatically through a stud feeder after each welding is completed. A water pump may be used to create a dry welding environment in the arc zone to ensure weld quality in some critical operations.

Details of the welding unit are as follows. The stud (8) to be welded to the plate (10) is contained within a metal chuck (15). The chuck (15) has two hooks (6) which hold the stud (8) with springs (14). The chuck (15) is attached to the spindle (7). The spring (5) is mounted along the spindle (7) and provides a compression force on the stud (8) when the stud (8) is pressed against the surface of a work piece (10) on which the stud is to be welded. A solenoid (4) provides the force which lifts the stud to initiate the arc between the stud (8) and the work piece (10). The bushing (1) is designed to include a circular electromagnet (11) in order to provide magnetic attraction to the work piece (10). The spring (14) is strong enough for the hook (6) to lift the stud (8), but weak enough that we can remove the welding unit from the welded studs. The ferrule (9) should last until all of the studs which are in the stud feeder (12) have been welded. The water pump (13) provides the water pressure to feed the studs from the stud feeder (12) to the chuck (15) through the flexible feeding pipe (3) and

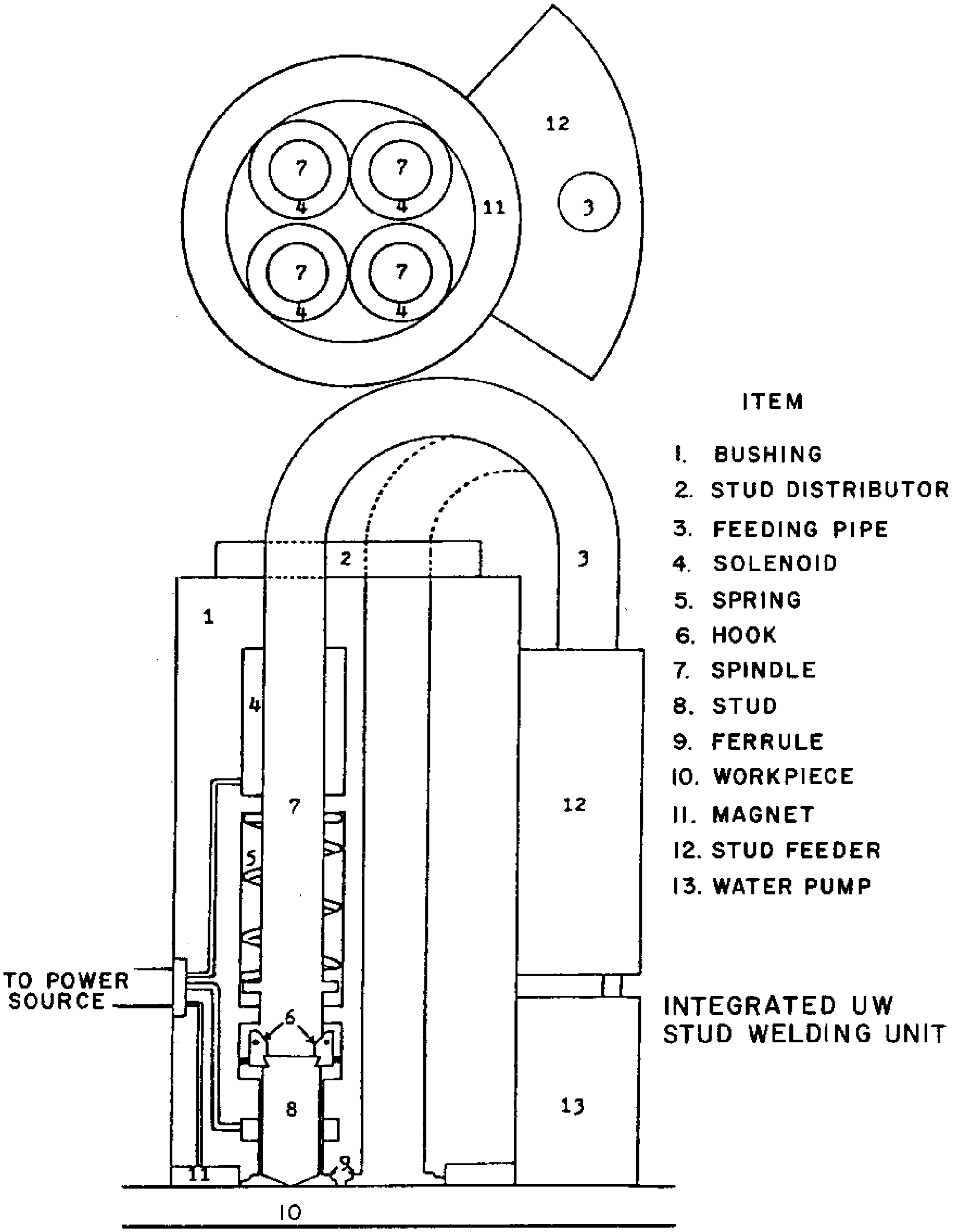


FIGURE 6-42 Conceptual design of integrated underwater arc stud welding system

the stud distributor (2) which distributes the studs to each chuck. The welding process is as follows:

First, the studs are fed from the stud feeder (12) with the water pressure of the water pump (13) and stop at each chuck (15). The switch of the electromagnet (11) is operated and the weld unit is attached to the workpiece (10) to which studs are to be welded.

Then the welding switch is operated, and welding process is accomplished as with the conventional arc stud welding gun. The solenoid (4) is energized to lift the spindle (7) up to a pre-set arc length. Thus, the stud (8) is withdrawn from the workpiece (10) drawing a pilot arc. After a pre-set time interval of arc, the power to the arc and solenoid (4) is cut, the spring (5) plunges the stud (8) into the molten area of the workpiece (10).

The welding process is repeated for each head with relays. After all of the welding processes are over, the switch of the electromagnet (11) is turned off. The welding unit is removed from the welded studs.

New studs are fed into each chuck and the unit is ready to work at the next site.

One example of many possible uses of the integrated stud welding unit is to lift a sunken ship in ocean salvage operations. Figure 6-43 shows an imaginary case of a salvage operation. An unmanned remotely operated vehicle carrying an underwater stud welding unit dives down to a destination on the sunken object, for instance, a disabled submarine. Stud welding is accomplished by remote control from the surface support ship. After welding is completed, lift ropes are attached to the unit. The vehicle moves to another location and repeats the operation. Finally, the support ship gathers the lift ropes and lifts the sunken object.

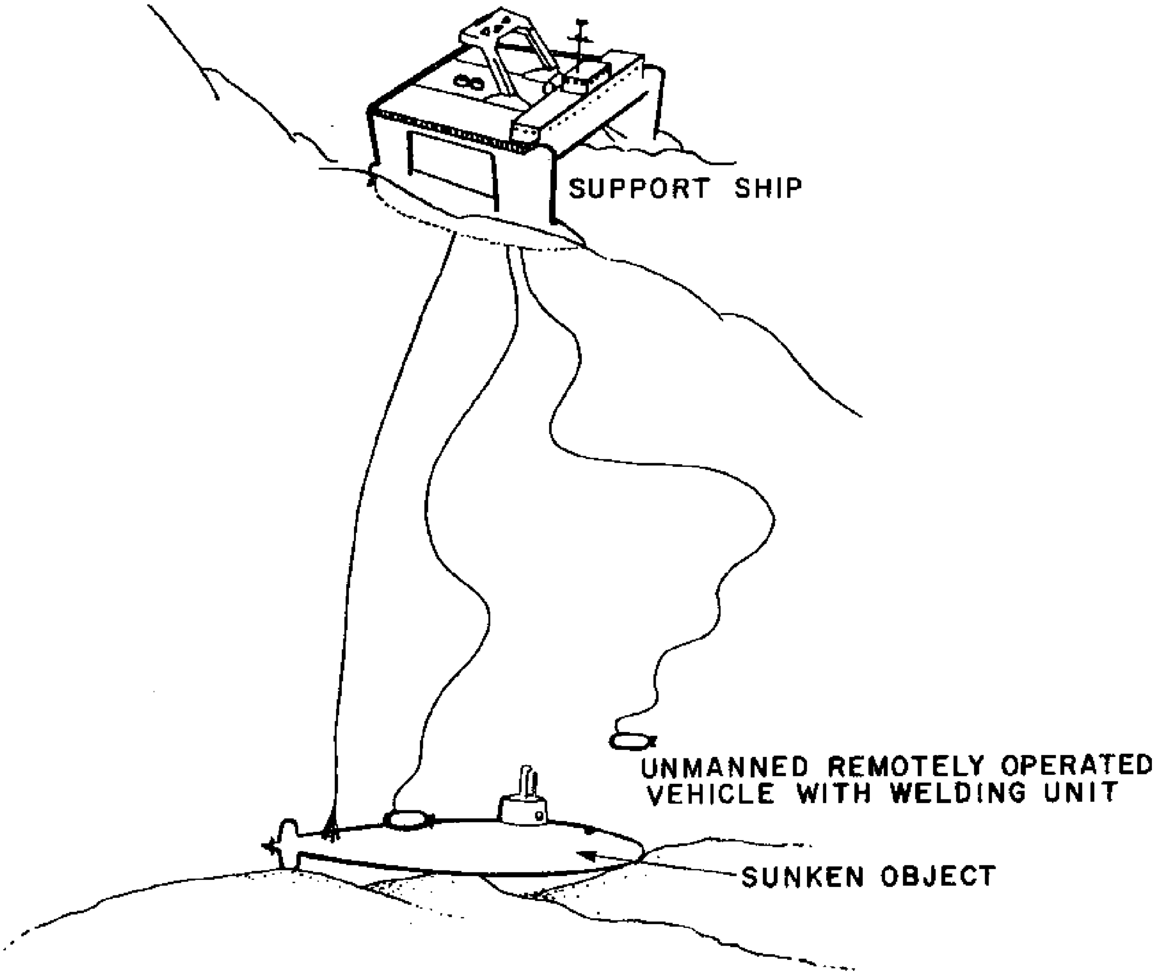
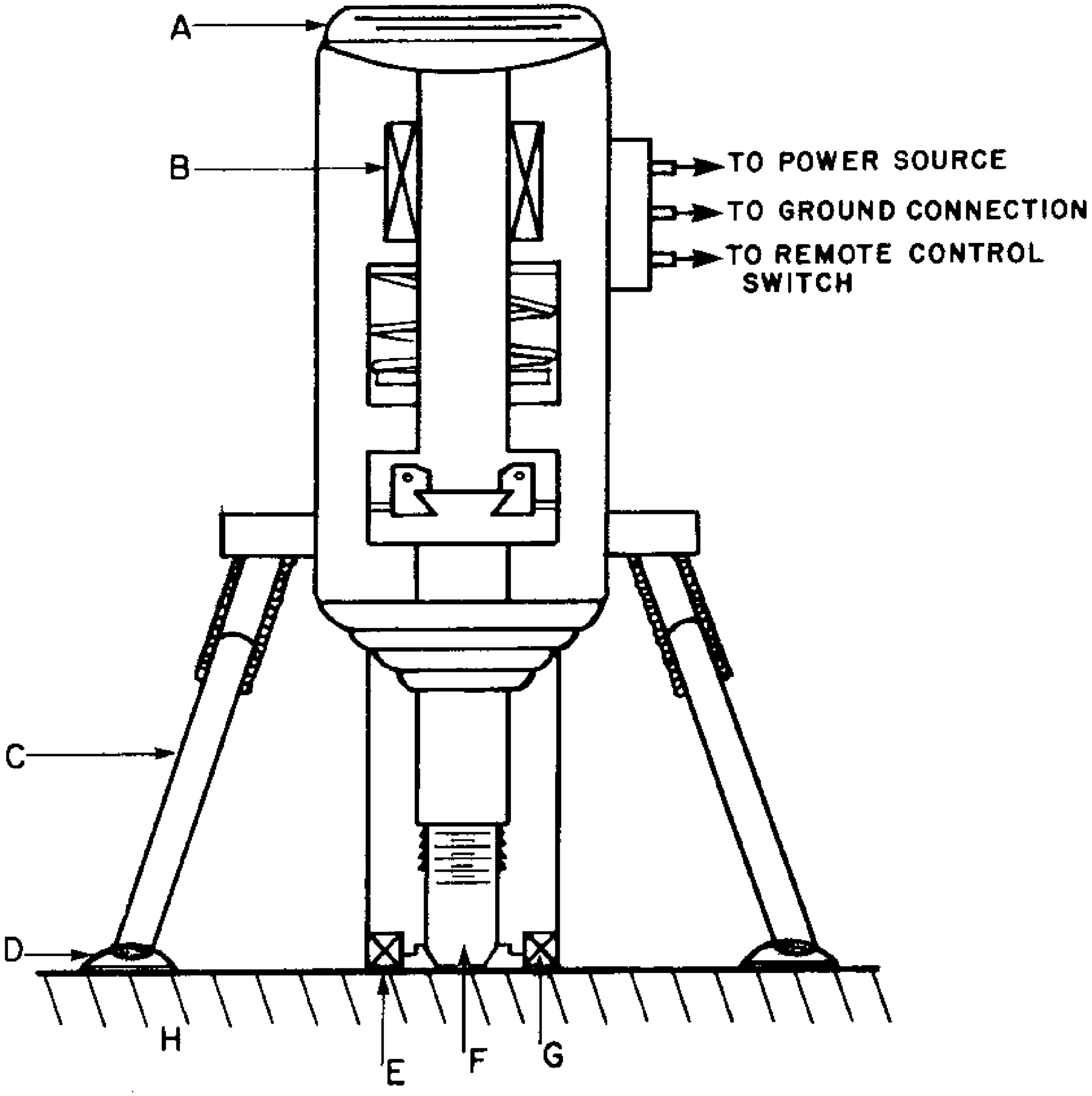


FIGURE 6-43 Application of integrated welding system for ocean salvage operation

6.5 Improvement of Design and Testing

Efforts were made to improve the initial design developed by Kataoka of an integrated underwater arc stud welding system. The efforts made primarily by Schechter and Schloerb included construction and testing of some important components of the stud welding system.

Figure 6-44 is an improved design of the integrated underwater stud welding system. A key to the successful operation of stud welding in deep sea is to be able to position the welding system in such a way that the stud is placed exactly vertically to the workpiece. The system must be held in that position until welding is completed. The foot support



A	ARC LENGTH CONTROLLER
B	SOLENOID
C	FOOT SUPPORT ROD
D	MAGNETIC SUPPORT
E	GROUND TO BASE PLATE
F	STUD
G	ELECTROMAGNETIC ARC CONTROLLER
H	BASE PLATE

FIGURE 6.44 A prototype underwater stud welding unit

rods (C) and the magnetic supports (D) are used to position the unit in a right location and in the right direction and securely hold the unit until welding is completed. The ground (E) is to provide a good ground connection necessary to make satisfactory welds. The electromagnetic controller surrounding the arc (G) is used to prevent any distortion of the arc under high environmental pressure. When the remote control trigger is pressed, the unit is activated and the solenoid lifts the stud to create a proper arc length and draws an arc between the tip of the stud and the base plate. It takes a fraction of one second to weld one stud.

6.5.1 Study by Schechter [T19].

Although stud welding has been used for various applications for many years, as described in 6.1, it has been used exclusively in air. Consequently, there is no commercially available stud welding gun which can be used in water. In the earlier experiments on underwater stud welding performed by Chiba and Kataoka test plates were placed in water but the stud welding gun was not immersed in water.

The first important task was to find ways to develop a stud welding gun which can be immersed in water. An important consideration here is how to make the gun safe to the operator. As shown in Figures 6-32 through 6-35, the arc voltage is about 50 volts but the welding current is over 1,700 amperes.

Initial Effort. It was decided to modify the existing KSM Safeguard Stud Welder, as shown in Figure 6-45. First, efforts were made to do the following:

(1) Seal the housing of the KSM Safeguard Stud Welder.

(2) Provide an air recovery system to eliminate the need for an air hose connected to the cylinder port.

(3) Provide remote control to eliminate the need for a diver.

The first two tasks were not designed with the deep sea applications in mind, rather they were intended to merely demonstrate the feasibility of the concept.

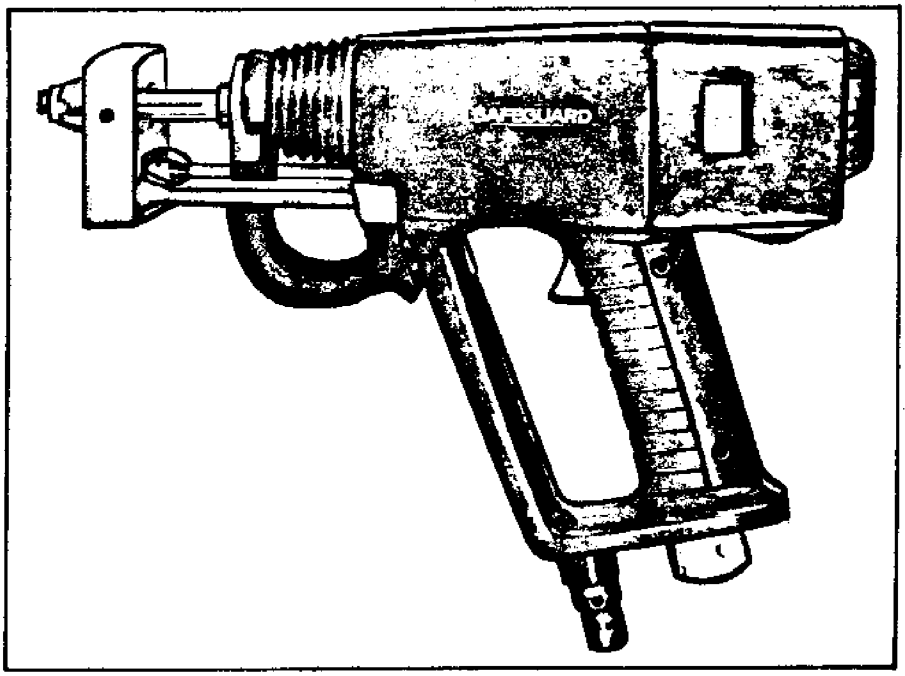


FIGURE 6.45 The KSM Safeguard Stud Welder

The work was accomplished in the following manner. The control and power cable connections were removed to several feet up the cable by adding in extra lengths of cable. The hole through which the control wires passed and the other unsealed places of the machine body were plugged and filled in with a resin plastic compound. For the air recovery system, copper tube was cast in plastic onto the body. The tube led from the cylinder port to the back side of the piston. This could provide a storage space for the expelled air and eliminate the vacuum created when the piston moved forward.

The welder was tested by making welds in a small tank of water. Several welds were made in air to adjust the setting of the power source, the KSM Powerhouse. Once this was done, ten studs were satisfactorily welded to steel plates underwater. The stud welder then failed, due to the presence of new electrical connecting wire inside the case. To protect the hardware, it was necessary to cast wires onto the empty case, and to connect the solenoid after the plastic had set. The researchers felt that the tests, though incomplete, were successful.

Rather than attempt to fix a difficult problem, the waterproofed stud welder was aborted. A number of reasons contributed to this decision:

(1) The new solenoid wires could not be eliminated.

(2) Unbalanced pressures of water and air acting on the stud would compress the mainspring, even when the solenoid was de-energized.

(3) Leaks could not be prevented at any appreciable pressure above atmospheric.

An entirely different approach to the problem was sought. The researcher acknowledges Mr. Charles Parker of the M.I.T. Stroboscopic Laboratory for his input to the solution. Simply stated, the working mechanism should work immersed in water, not protected from it.

The Water Floodable Stud Welder. The main goal was to construct a stud welder that need not be sealed from its environment in any way. It was to be based on the components of the KSM Safeguard Stud Welder. Translating this into specific criteria:

(1) Redesign the housing of the KSM Stud Welder to be an open framework rather than a sealed case.

(2) Modify the working mechanism so that it may be mounted in the new frame.

(3) Modify the piston-cylinder mechanism to operate in water.

(4) Modify the solenoid to operate in water.

In addition, a ferrule positioning device was designed and added to the machine. Details of the work performed by Schechter were described in his report [T19].

When the machine was completely assembled, tests were made to determine the success of the work. Welds were made in air first. When satisfactory welds were made, the water test was set up. Welds were made with only the chuck in water until they were of reasonable quality. Water was added to the tank to cover the flood part to the cylinder. The weld cycle was triggered and the arc was drawn. However, the single flood port did not allow the plunge to proceed quickly enough and the molten pool of metal and the molten stud tip solidified before being pressed together. Two more flood ports were made. Reasonable welds were then made. More water was added to the tank to fill the working mechanism behind the piston, but not up to the solenoid. Reasonable welds were made in this condition. The testing went no further.

6.5.2 Study by Schloerb

The work conducted by Schechter is being continued and expanded by Schloerb who plans to prepare an M.S. thesis in May 1981. Since his work has not been completed when this report is written, we plan to present details of his work in a later report covering the work conducted under a new program entitled "Development of Fully Automated and Integrated ("Instamatic") Welding Systems for Marine Applications". The outline of the work being performed by Schloerb is presented here. Figure 6-46 shows schematically an integrated stud welding system being developed. Further details are as follows.

Stud Lifting Mechanism. This mechanism is the heart of the machine. When activated, it lifts the stud a predetermined distance. This occurs simultaneously with initiation of the electric arc between the stud and the work piece. The result is that welds are made with a uniform arc length.

Both the lifting mechanism and the welding current are controlled by an electronic controller, which may be placed away from the machine. For example, the controller may be placed above water in case of underwater welding. The control unit also controls the duration of the arc.

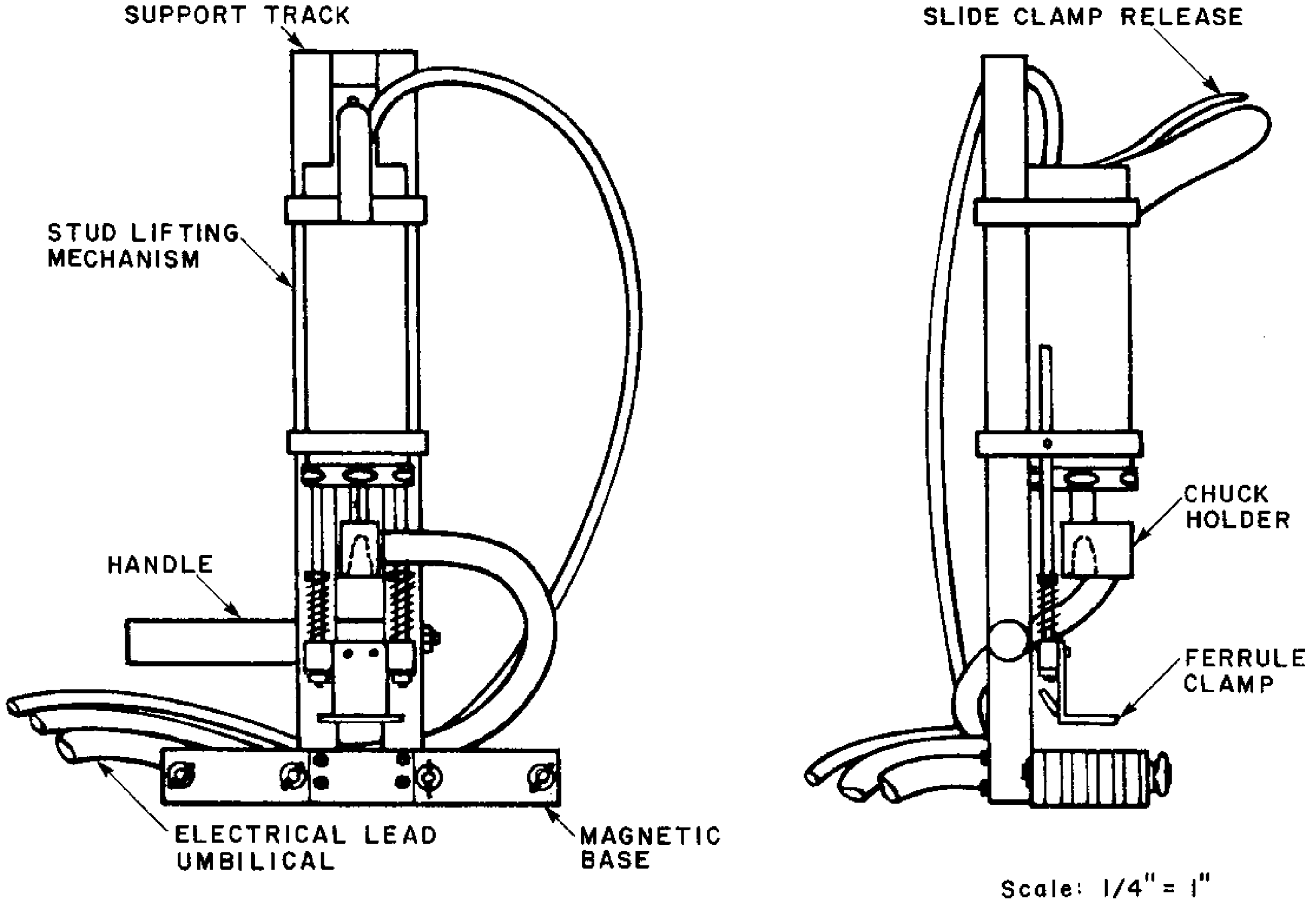


FIGURE 6-46 Instamatic stud welding machine

After a predetermined time the welding current is stopped and the lifting mechanism plunges the stud into a puddle of molten metal on the work piece. The molten metal solidifies quickly and the weld is made.

The key components of the lifting mechanism are (1) a solenoid to lift the stud, (2) a spring to plunge the stud into the molten metal puddle, and (3) a lifting rod to transmit the force of the solenoid and the spring to the stud. The lifting rod is supported by linear bearings which prevent lateral motion of the stud. Also a clutch mechanism is employed to insure that the stud is always lifted the same distance regardless of how much the spring is compressed prior to activation of the solenoid. Note that initially the spring must be partially compressed, because the end of the stud melts away during the arc process. This makes the stud shorter so that it must plunge back further than it was lifted.

Two key factors, electrical safety and corrosion resistance, were taken into account in developing a stud lifting mechanism which could be used underwater. The principal approach to dealing with these factors was to redesign the mechanism so that much of it could be built out of plastic. In addition, an effort was made to make the design as simple as possible. One key factor of the design is that it is "water floodable" rather than water proof, thus making it inherently adaptable to deep-sea applications.

Chuck Holder. The chuck holder serves as the hot electrical connection to the stud. It is designed to adapt to conventional chucks presently used with land stud welding equipment. The chuck holder is attached to the lifting rod by a cheap "break-away" fitting which would prevent the lifting mechanism from damage in the event that excessive torque is applied to the stud.

Side Clamp Release. The stud lifting mechanism is designed to slide up and down on the support track. A spring clamp locks the mechanisms at any point along the track which is desired. This clamp is released by squeezing the handle at the top of the lifting mechanism. In normal operation the operator, who will be a diver in the case of underwater welding, presses down on this handle to cock the main spring. Then he will pull up on the handle in order to release the chuck from the stud after it has been welded in place.

Ferrule Clamp. A disposable ceramic ferrule is clamped around the base of the stud to prevent splatter of the molten metal during the welding process. This is very important in the case of underwater welding, but it is unrealistic to expect a diver to handle these small ferrules. (Note: Divers frequently find themselves in situations where they cannot see and they try to feel with numb hands through heavy rubber gloves.) The ferrules are press-fit on the end of the studs. This is done by wrapping the end of the stud with steel wool and then forcing the stud over the steel wool. In addition to holding the ferrule in place, the steel wool also serves as an arc initiator. While this eliminates the problem of handling the ferrule underwater, it also poses a new problem in clamping the ferrule in place during the welding operation. The problem is that a conventional (rigid) ferrule clamp tends to knock the ferrule off the end of the stud (causing it to be lost) when the stud is loaded into the chuck. This happens because the main spring is compressed as the stud is pressed into the chuck. One solution to this problem is a ferrule clamp which is free to move up with the ferrule while the stud is being loaded, but which locks in place as the mechanism is being cocked.

Magnetic Base. The concept of using a magnetic base was developed originally for underwater applications of stud welding. This concept can be used for many applications of instamatic stud welding. For example, the magnetic base is useful for placing the stud in the vertical position in welding a stud to a curved plate (see Figure 7b of the proposal). By use of the magnetic base it is possible to securely hold the stud welding gun in place so that the gun can be activated by a remote control mechanism. The original concept for an underwater application is described below.

One major difference between a land stud welding machine and an underwater machine is that the underwater machine needs to be activated remotely from the surface. This does not mean that the diver leaves the water when the machine is activated, only that he does not activate it himself by pulling a trigger the way an operator on land would. This is done for reasons of electrical safety and to make the system more reliable. It creates a problem, however, in that the diver does not know exactly when the machine will be activated. Without some means of clamping the machine to the work piece, the diver would be forced to hold the machine steady for a relatively long time while waiting for it to be activated.

A magnetic base is a good solution to this problem. It also has an added advantage due to the fact that divers frequently encounter situations where they lack leverage. Not only does the magnetic base make it unnecessary for the diver to press the machine against the work piece, even for a short time, but it can also provide a place for the diver to hold on. In addition, it serves as an electrical ground connection to the work piece.

The magnetic base is assembled from an alternating series of standard ceramic magnets and steel plates. The assembly is clamped together in normal operation by bolts and wing nuts. The wing nuts can be loosened so that the base can conform to a curved surface such as a pipe. The magnets are held in place by plastic retainers when the nuts are loose.

Support Track. Support track is constructed from two pieces of PVC (polyvinyl chloride) pipe. The ready availability and low cost of PVC makes replacement of this component relatively easy. This design has the added advantage that the machine can be refitted to suit a particular job. If extra long studs are to be welded, then the track can be made shorter so that the diver only needs to carry along what is needed. The support track also provides an ample lever arm for releasing the magnetic base.

Handle and Electrical Lead Umbilical. The main hand hold is attached to the support track as near as possible to the magnetic base. This is done to minimize the possibility that the diver will accidentally cause the base to release from the work piece by pulling on the handle too strongly. The electrical umbilical is attached near the base for the same reason.

It is also desirable to have the handle near the umbilical attachment point in order to minimize unwanted torques on the divers hand when he is moving the machine from place to place. It should be noted that, in some situations, simply tugging the umbilical from one point to another may involve considerable effort.

6.6 Summary and Conclusions of the Work on Stud Welding

(1) The arc stud welding can be used successfully underwater. For shallow-water applications, presently available welding systems appear to work satisfactorily provided that they can be immersed in water. For applications in deep-water (say, 100 feet or more), however, special efforts should be made (a) to make sure that the arc initiate all the time and (2) to protect the arc from disturbances caused by high pressure.

(2) In the mechanical and metallurgical examinations, including tensile tests, bend tests, examinations of macrostructures and microstructures, and microhardness tests, underwater welded specimens exhibited properties comparable to those of welds made in air. The major reason for the good quality of underwater stud welding is that unlike underwater "wet" arc welding in which metal particles must travel in water the surfaces to be joined in the stud welding are not directly exposed to water. The application of pressure in a later stage of stud welding helps to squeeze out some of the weld metal and reduce porosity and other inperfections.

(3) Underwater stud welding can be used not only for low-carbon steel but also high-strength steels. Since the surfaces to be joined are not directly exposed to water, metals near the weld are not subjected to rapid cooling; therefore, it is possible to prevent the formation of undesirable, brittle metallurgical structures inherent to "wet" underwater arc welding.

(4) It appears that no sophisticated systems, such as a dry chamber for water evacuation from the welding site or gas shielding equipment are needed in order to obtain welds with good quality. We believe that it is possible to develop a relatively simple system which will work satisfactorily in deep sea.

(5) An important step in the development of the abovementioned system is to design and construct a stud welding gun which can be immersed in water. Since there is no commercially available stud welding gun which can be immersed in water, efforts have been made to develop such a system. Since the current and voltage needed for welding a large stud (say 3/4 inch in diameter) are quite large (approximately 1,800 amperes and 50 volts), it is difficult to develop a gun which can be operated safely in water. An initial effort was to develop a water-tight system. Later efforts were directed toward developing a water floodable gun. The work has not been completed within the period of this research. The work is being continued and we hope to report the results of the work in the future.

CHAPTER 7

DEVELOPMENT AND TESTING OF FLUX-SHIELDED WELDING SYSTEMS

As described in Chapter 5 Erickson demonstrated that the flux-shielded arc welding process could be used satisfactorily underwater under pressure. Efforts were made (1) to develop a conceptual design of an automatic underwater welding machine and (2) to construct some key components of the machine. The efforts were made primarily by Lombardi [T18].

7.1 Development of a Conceptual Design

Figure 7-1 shows the general concept of the prototype unit. For deep-sea applications the entire unit shown here probably needs to be installed in a watertight, strong vessel. The machine consists of a motorized carriage which simultaneously provides the consumable electrode wire feed into two torches, and the travel of the wire. These electrodes are connected to a surface power supply via cables. The cables are enclosed by a larger cable which is fastened to the top of the machine's frame using a waterproof coupling. A plate to be welded is placed securely between the torches parallel to the line of travel. Stainless steel foil molded at the base of the plate holds the shielding flux and keeps it dry. The mechanical parts of the machine are enclosed by a bottomless metal frame. The rim of the open face of the frame is lined with a thick rubber strip to provide a means of attachment to a steel surface.

Operation of the machine is simple (see Figure 7-2). The machine, after being placed upon a steel object on which welding will take place, is evacuated of all water creating a local dry environment. This is done by forcing water from the surface down through a valve containing a series of pivot tubes. The velocity of the water will cause the water to be sucked out of the box through the valve. This in turn will force the rubber gasket to form a tight seal on the steel workpiece.

The motor and torches are then activated simultaneously. The wire

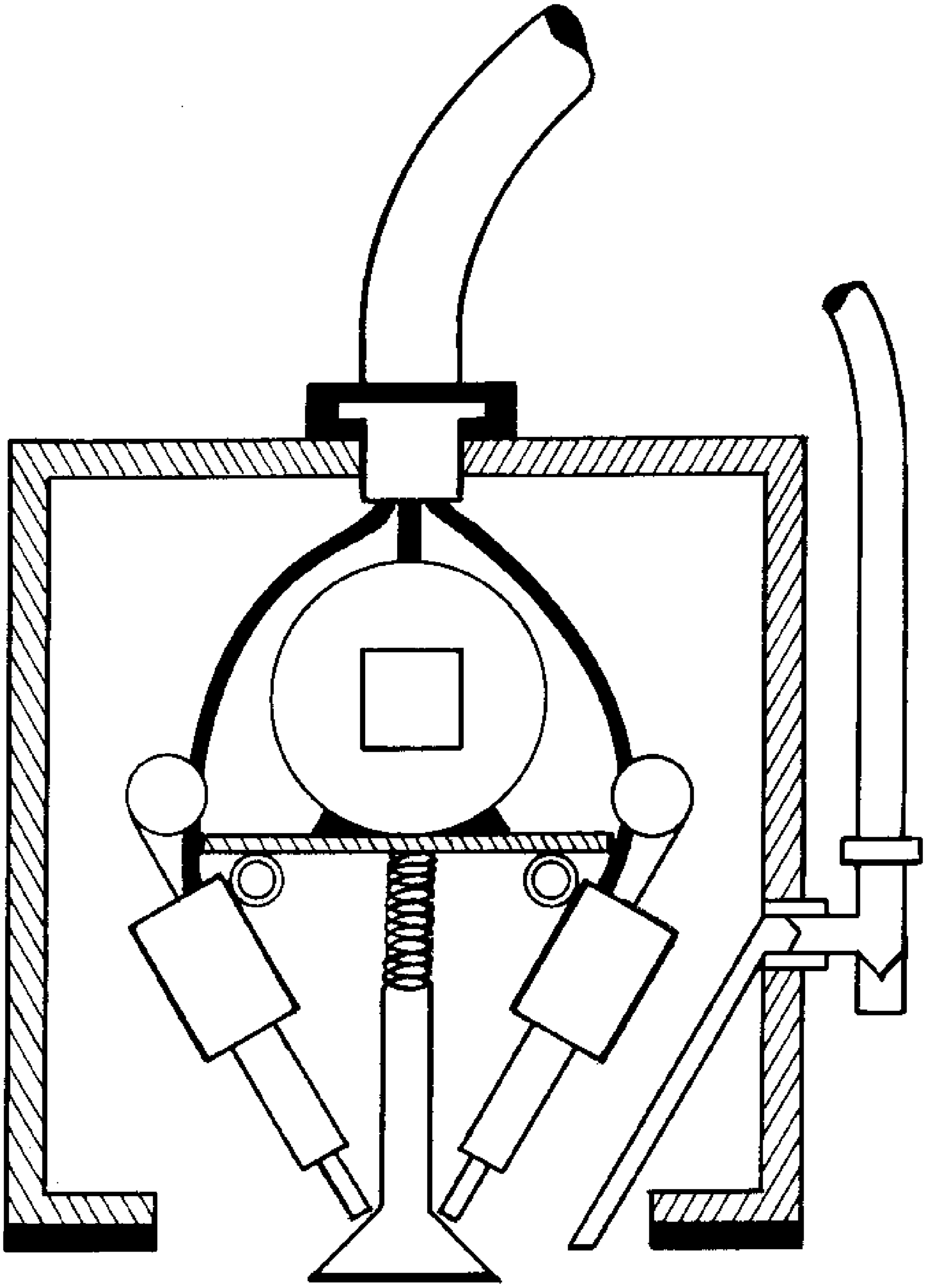


FIGURE 7-1 Conceptual design of automatic underwater welding machine

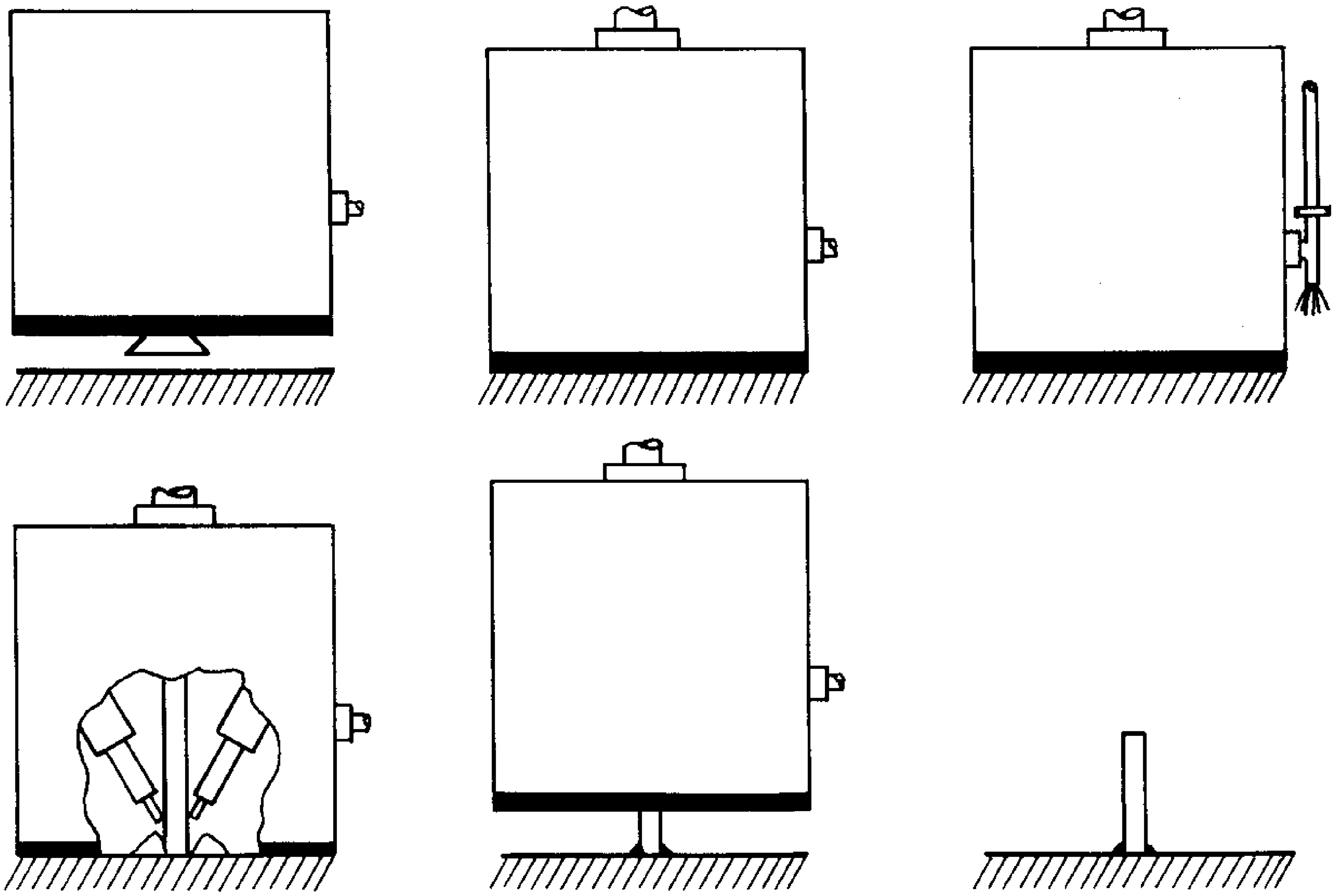


FIGURE 7-2 Welding procedure sequence of automatic underwater welding machine

coming through the torches becomes electrically charged and an arc is drawn between it and the workpiece. The arc, being of high amperage, will burn through the foil and be contained within the shielding flux. As the torches pass along the intersections of the two plates, a double fillet weld is produced.

The carriage automatically stops after the full length of the plate has been travelled. The frame can then be flooded and the machine removed due to the loss of suction. The plate will be left welded to the metal object.

7.2 Design, Construction, and Testing of a Prototype Machine

Efforts were made to design, construct, and test a prototype machine. The automatic underwater welding machine being developed has two important and unique features as follows:

(1) The machine is completely enclosed and welding is performed by merely pressing a button. Although a trained person may be needed to assemble the machine, no skill or training is needed to operate the machine.

(2) The plate to be welded is contained in a "cassette" which is attached to the machine, and when welding is completed and the machine is removed the plate welded to the workpiece will be detached from the machine.

These features are radically different from what is normally done in welding today. Firstly, manual arc welding requires a specially trained welder. Even automatic welding machines are operated by specially trained people. Secondly, in the current practice of arc welding, plates to be welded are first assembled together and a welder or a welding machine comes to the weld location to perform the necessary welding operation.

It was decided that a prototype machine be designed and constructed to prove that these features could be achieved. Because of restrictions of the parts commercially available the machine actually constructed was not a prototype of a machine to be used deep-sea but rather a machine which proves that these features are achievable. Figure 7-3 shows a sketch of the complete machine assembly, of which major components are:

1. The drive system which includes the motor, gears, sprockets, and chain
2. The carriage
3. The wire feed mechanism
4. The torch manipulator
5. The frame
6. The carriage receptacle
7. The electrical system

Details of these components are described in Lombardi's thesis [T18]. Figures 7-4 a and b show a side view of the welding assembly and a close-up of welding heads for fillet welding, respectively.

After the welding assembly was completed a series of tests were made. Tables 7-1 and 7-2 show welding conditions used in the tests including welding current, arc voltage, arc travel speed, and arc length. The test welds were examined by visual inspection as well as inspections of macro and microstructures. Results of the examinations are presented in Lombardi's thesis. Figures 7-5 through 7-8 show cross sections of four welds. As shown in these figures fillet welds with good quality were obtained with this prototype machine.

Because of the limitations of time and funds available no further study was conducted. Although we could not build a machine which could be used for deep-sea underwater welding, we were able to build a completely automatic welding machine which could make a double fillet weld by merely pressing a button. Such a machine could be further developed to an automatic welding machine, as shown in Figure 7-1, which can be operated underwater under pressure.

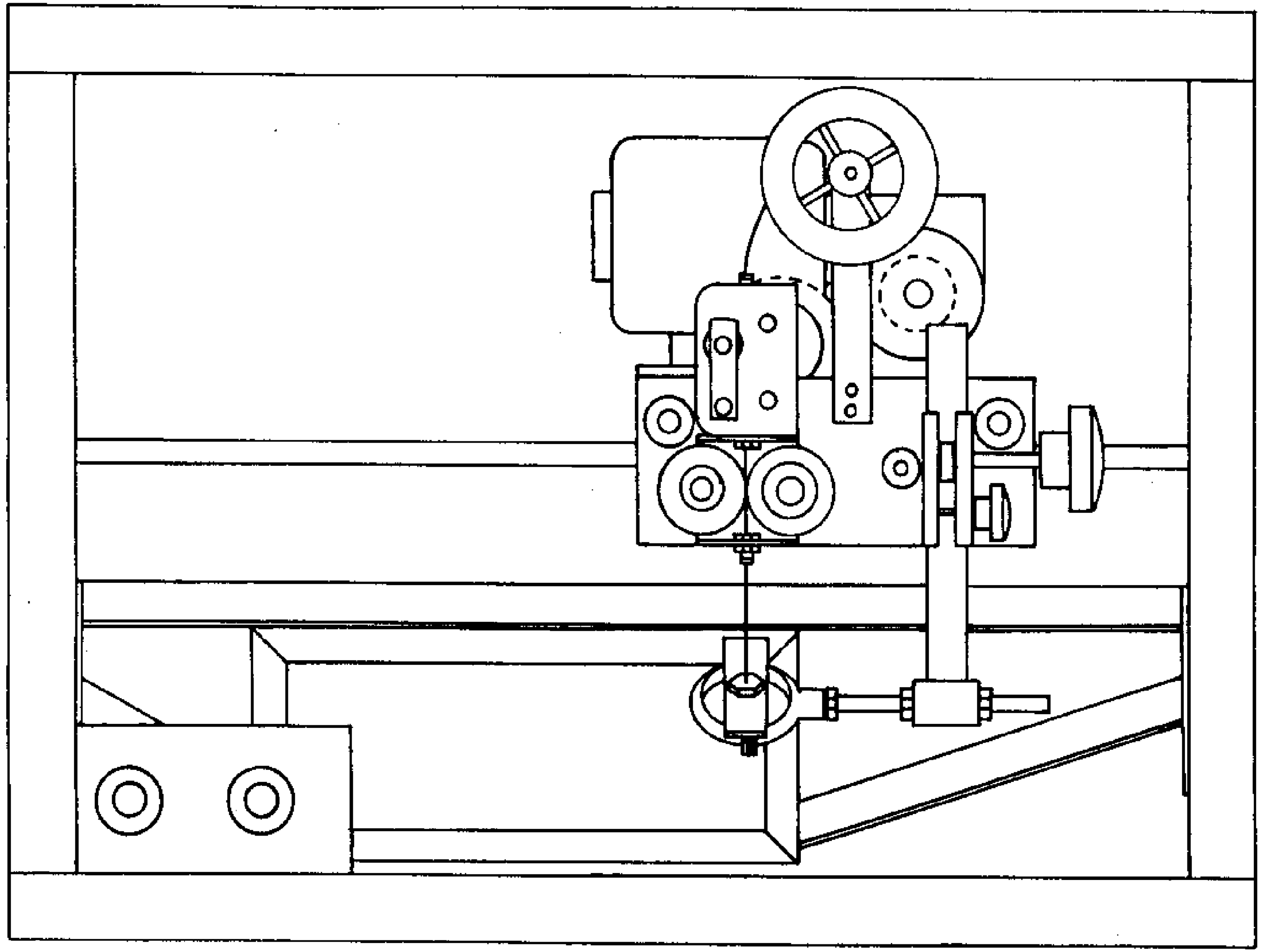
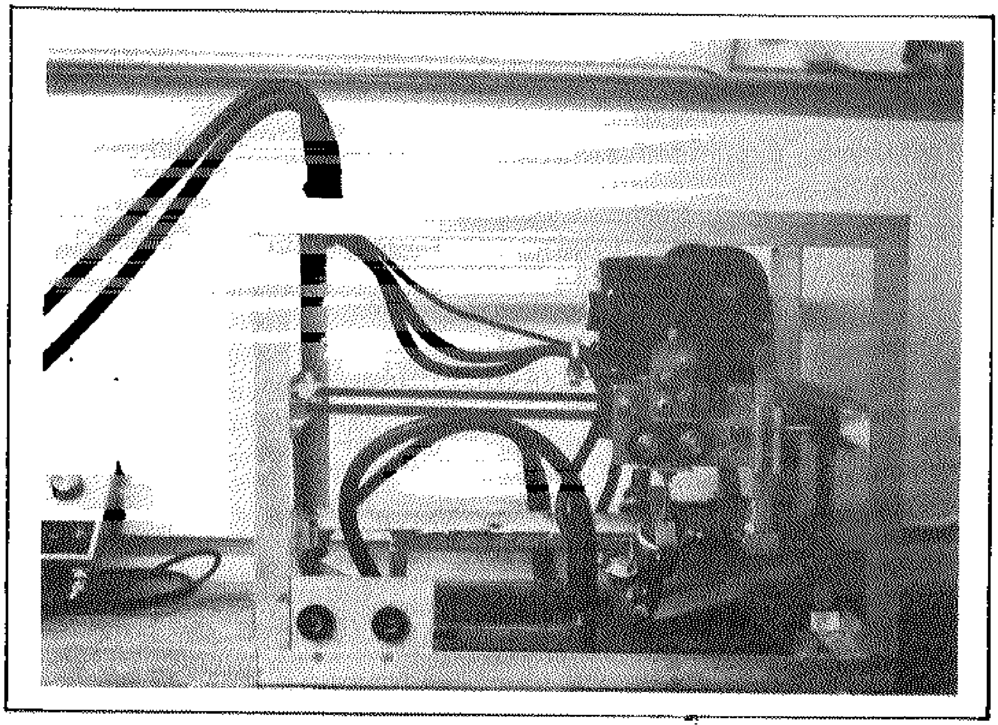


FIGURE 7-3 Complete machine assembly (1/4 scale)



a. WELDING
ASSEMBLY

b. CLOSE-UP OF WELDING HEADS
FOR FILLET WELDING

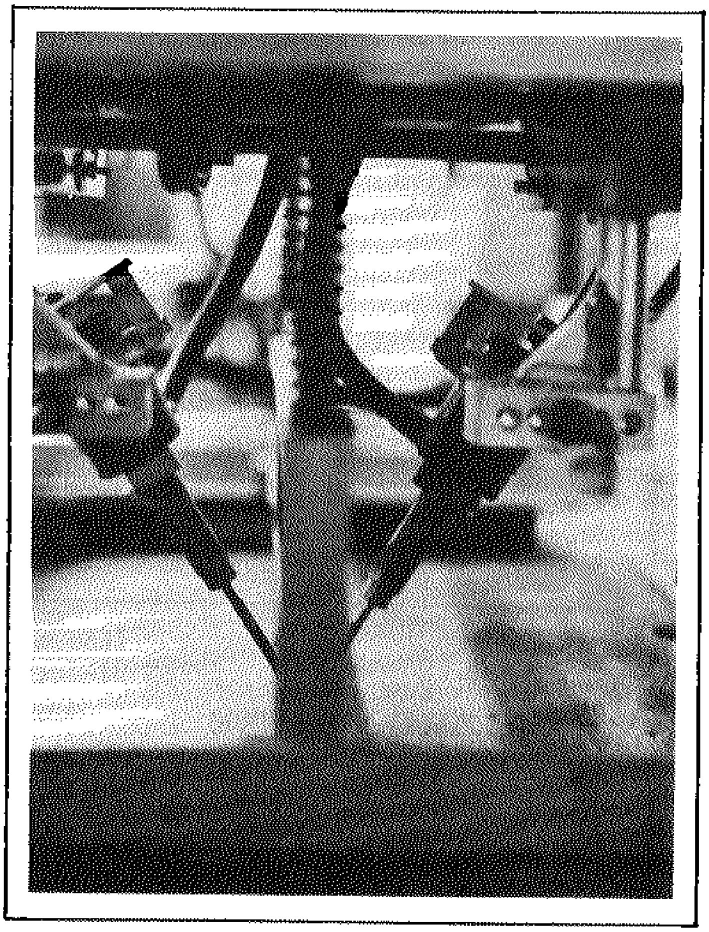


FIGURE 7-4 Photographs showing an assembly for fillet welding

TABLE 7-1 Experimental data on flux-shielded process

ARC LENGTH 1/4-inch

TEST 1
SPEED 56-1/4-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
-		-	300		33
250		30	-		-
300		30	300		31

TEST 2
SPEED 62-1/4-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
350		30	300		30
350		30	350		30
350		30	350		30

TEST 3
SPEED 69-3/4-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
400		27.5	350		27.5
350		30	350		30
400		27.5	380		29

TEST 4
SPEED 76-1/2-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
400		27.5	400		27.5
380		27.5	400		27.5
380		27.5	380		27.5

TEST 5
SPEED 81-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
400		27.5	400		27
400		27.5	400		26.5
400		27.5	400		27

TABLE 7-2 Experimental data on flux-shielded process.

ARC LENGTH 3/8-inch

TEST 6
SPEED 56-1/4-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
300		33	300		33
300		33	300		33
300		33	300		33

TEST 7
SPEED 62-1/4-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
310		30	300		33
300		33	300		32.5
300		32	300		33

TEST 8
SPEED 69-3/4-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
340		30	320		31
340		31	320		31
340		30	340		31

TEST 9
SPEED 76-1/2-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
360		29	360		30
360		30	350		30
360		30	360		30

TEST 10
SPEED 81-inch/min.

AMPERAGE	LEFT	VOLTAGE	AMPERAGE	RIGHT	VOLTAGE
380		28	400		27.5
380		29	-		-
400		27.5	400		28

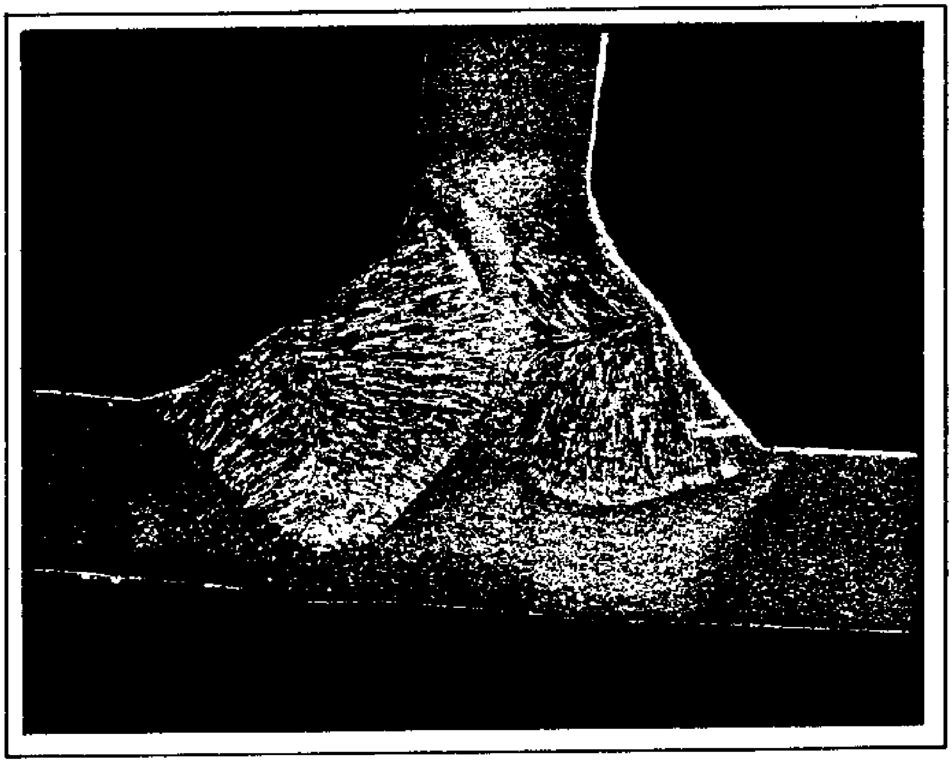


FIGURE 7-5 Micro and macro structures of fillet weld arc length 3/8 in. speed 56 1/4 in./min.

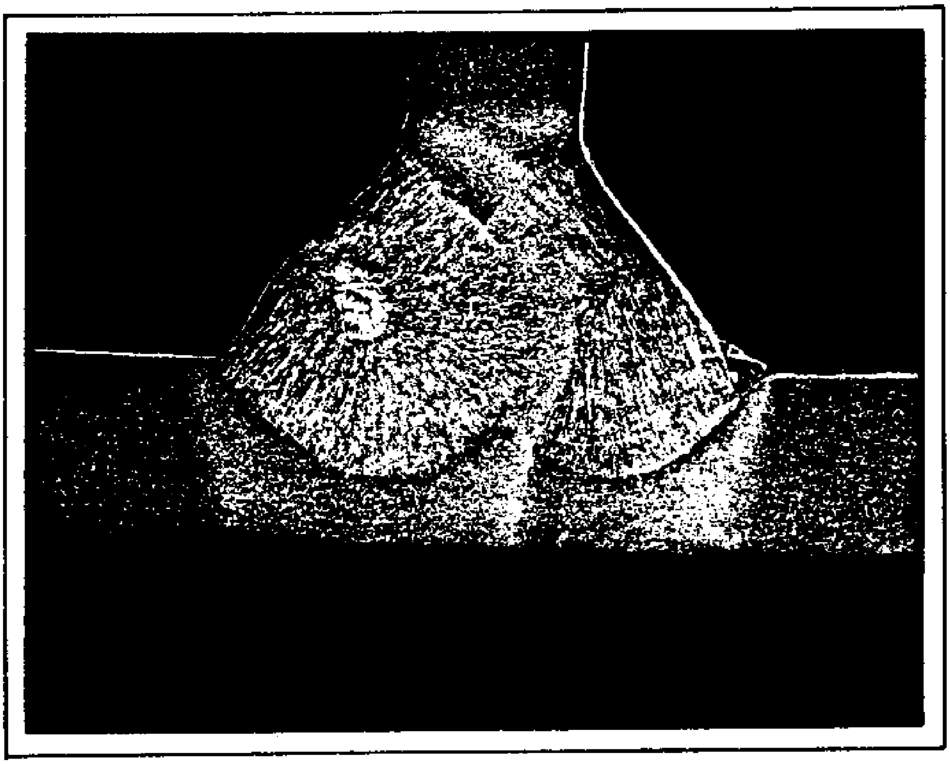


FIGURE 7-6 Micro and macro structures of fillet weld arc length 1/4 in. speed 62 1/4 in./min.

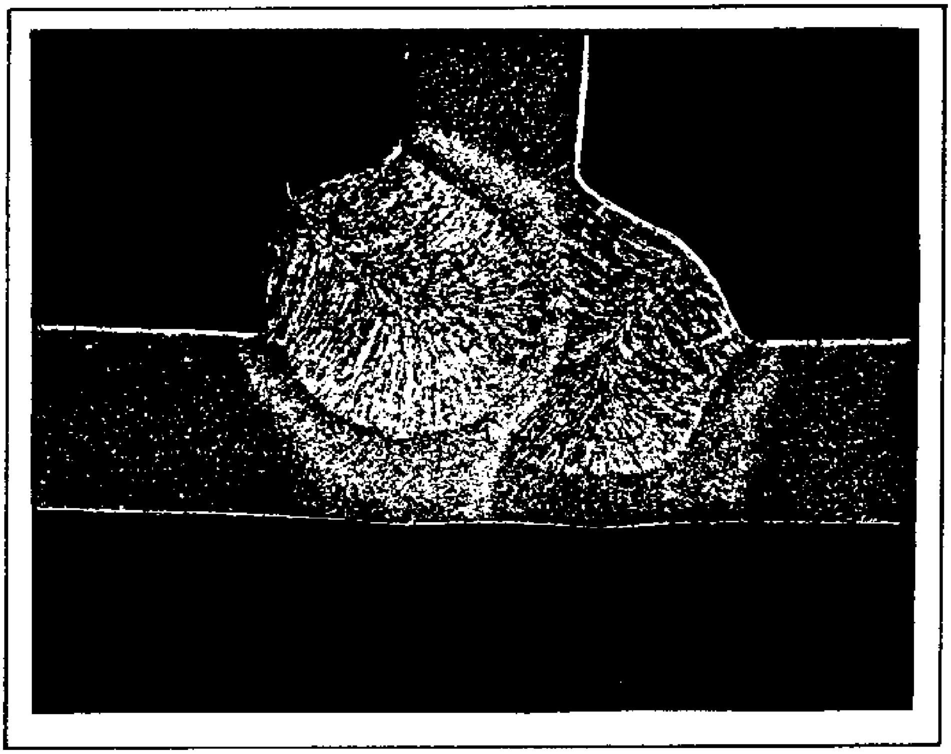


FIGURE 7-7 Micro and macro structures of fillet weld arc length 1/4 in. speed 76 1/2 in./min.

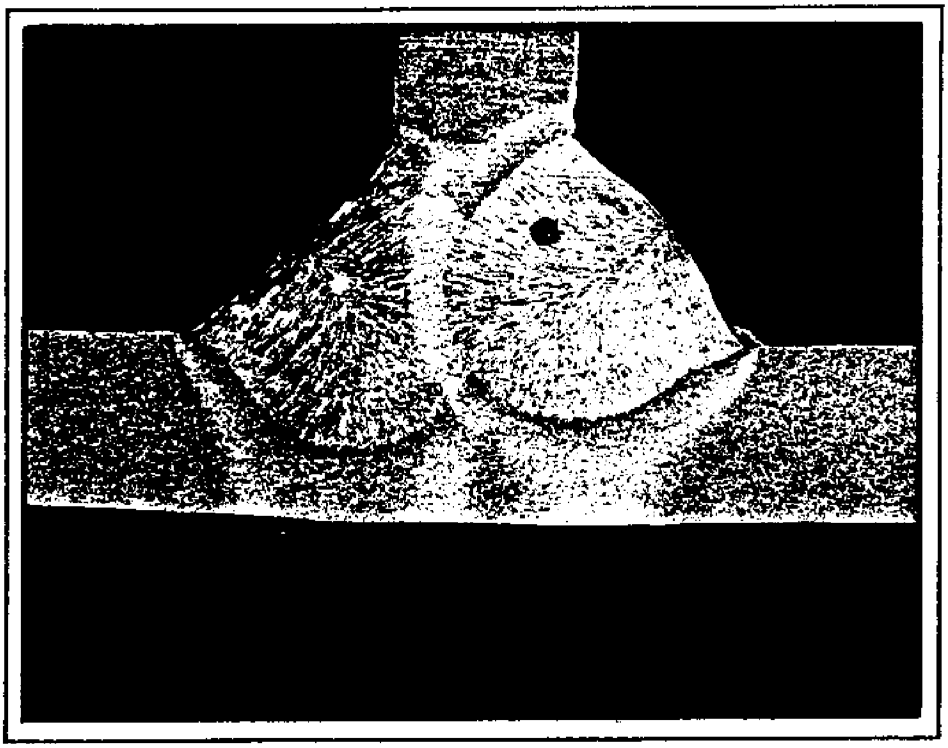


FIGURE 7-8 Micro and macro structures of fillet weld arc length 3/8 in. speed 76 1/2 in./min.

7.3 Continuing Efforts

Efforts are being continued at M.I.T. to further improve the push-button automatic welding machine. The current efforts are aimed at developing a series of fully automated and integrated welding systems, which may be called "instamatic" welding machines. They can be used not only for underwater welding but also many other applications.

During this research program for deep-sea underwater welding, M.I.T. researchers studied various ways to develop fully automated and integrated systems which can be operated by people with no welding skill. They became convinced that similar systems can be developed for many applications other than deep-sea underwater welding. In fact, development of welding systems in dry environment is much simpler than those which must operate underwater, especially in deep-sea. As far as the number of potential uses of welding systems is concerned, there will be far more cases where instamatic welding systems are needed than deep-sea underwater welding, which is a very specialized application. An interesting concept developed during the current research is the idea of an enclosed welding unit containing a piece to be welded in a "cassette". This idea is a rather radical departure from the current concept and practice. In the current practice of arc welding, plates to be welded are first assembled together and a welder or a welding machine comes to the weld location to execute welding.

Over the years efforts have been made by many companies to develop automatic welding machines which can be operated very easily. Efforts also have been made to make small welding machines. As a result, M.I.T. researchers were able to conduct welding experiments in the pressure tank by remote control and develop automated and integrated welding units during the current research program. What has been lacking in the welding industry is the concept of the "instamatic" welding system containing a piece to be welded in a "cassette". This is probably due to the fact that welding companies always assume that skilled welders are available.

Many small-size automatic welding machines which can be used as parts of "instamatic" welding systems already exist; however, there is no indication of developing "instamatic" welding systems.

On the other hand, when one examines modern products other than welding, such as cameras and tape recorders, the concept of "instant" and "cassette" is very common. In the case of cameras, for example, "instant" cameras were introduced rather recently (perhaps in the 1960's). During the early years of instant cameras some expert photographers were not impressed by instant cameras which could only produce photographs of rather low quality. However, instant cameras have been improved considerably during the last several years, and some recent models can produce photographs of fairly high quality. An important development which took place is the phenomenal increase in the number of cameras on the market. Many families now have several cameras within one family.

Today there are a number of simple-to-operate products including cassette tape recorders, electronic calculators, etc. A unique characteristic of these simple-to-operate products is that they are the products of careful engineering and the applications of sophisticated technologies. As a result of careful engineering, simple-to-operate tools can be developed which can perform functions which normally require skilled persons. A good example is the Polaroid SX-70 camera which produces colored photographs instantly by merely pressing a button. This product has been developed as a result of a large scale marketing as well as research and development effort.

M.I.T. researchers are convinced that "instamatic" welding units for various applications can be developed (see 8.2 for further discussions).

7.4 Summary and Conclusion of the Work on Flux-Shielded Welding

(1) A conceptual design of an automatic underwater welding machine which could be used in deep-sea has been developed.

(2) A simple automatic welding machine which can be operated by merely pushing a button has been constructed and tested.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 Conclusions

Since summaries of the work done under Tasks 1 through 7 are already described at the end of the chapters discussing these tasks, overall conclusions drawn in this research program are presented here.

Most of high quality welding jobs which must be performed in deep-sea today are done by the dry chamber processes, as stated in 3.3. However, they are extremely expensive due largely to the high cost of using dry chambers in deep-sea. Wet manual shielded metal arc welding is not suited for deep-sea applications because:

(a) The qualities of welds made by the "wet" process are not satisfactory in the first place due to the direct exposure of the weld to water.

(b) The manual SMA requires skilled manipulation of the electrode. As the depth increases it becomes increasingly difficult for the diver/welder to perform the skilled manipulation of the electrode.

Therefore, it is extremely important to develop integrated and automated welding systems which satisfy the following requirements

(1) Joining must be performed without having direct contacts between the metals being joined and the surrounding water.

(2) The machine should be fully integrated. Skilled personnel may be needed to assemble the machine on board the support ship. However, no skill should be required for activating the machine. In fact, the machine can be remotely controlled, and all the diver must do are to place the machine and inform the personnel on the support ship to activate the machine.

Efforts were made to develop integrated and fully-automated machines using two welding process: stud welding and flux-shielded arc welding. Since the stud welding is a simple, fully-automated process it was possible to demonstrate that it can be successfully used underwater under pressure. We believe that the best way is to design a water floodable stud welding gun. Some efforts have been made to develop a water floodable stud welding gun.

Efforts also have been made to develop an integrated, fully-automated welding machine using the flux-shielded process. A conceptual design of an automatic underwater welding machine which could be used in deep-sea has been developed. A simple automatic welding machine which can be operated by merely pushing a button has been constructed and tested.

8.2 Recommended Future Research

(1) Stud Welding. On the basis of results obtained in this research program it appears to be quite possible to develop integrated and fully-automated stud welding systems which can be used for deep-sea applications. It is recommended that efforts be continued to design and construct actual hardwares.

(2) Development of "Instamatic" Welding Systems. During this research program studies were made of various ways to develop integrated and fully-automated systems which can be operated by people with no welding skill. We believe similar systems, which may be called "instamatic" welding systems, can be developed for many applications other than deep-sea underwater welding. In fact, development of welding systems in a dry environment is much easier than those which must operate underwater, especially in deep-sea. These systems which need to be developed through careful engineering will be able to perform certain prescribed welding jobs by a person with no welding skill. In many cases welding will be performed in a completely enclosed system so that no spark and very little fume will be

generated from the welding system. These welding systems can be successfully used for various applications, some of which are listed as follows:

(a) Certain repair jobs on board a ship and salvaging jobs which must be performed when no skilled welder is available.

(b) Certain welding jobs which must be performed in a compartment where sparks from the welding may cause fire or explosion.

(c) Certain welding jobs which must be performed in hazardous environment making it difficult or impossible for them to be performed by human welders.

The current research program that started on July 1, 1980 is aimed at developing these "instamatic" welding systems.

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APPENDIX A

U.S. PATENTS ON UNDERWATER WELDING GRANTED TO M.I.T. RESEARCHERS

A.1: U.S. Patent #3,989,920 "Underwater Stud Welding Gun"

A.2: U.S. Patent #4,069,408 "Method and Apparatus for Underwater Submerged Arc Welding"

APPENDIX A.1

United States Patent [19]
Masubuchi et al.

[11] **3,989,920**
[45] **Nov. 2, 1976**

[54] **UNDERWATER STUD WELDING GUN**

[75] Inventors: **Koichi Masubuchi,** Arlington, Mass.; **Muneharu Kutsuna,** Takarazuka, Japan

[73] Assignee: **Massachusetts Institute of Technology,** Cambridge, Mass.

[22] Filed: **May 15, 1975**

[21] Appl. No.: **577,582**

[52] **U.S. Cl.** .... **219/98;** 61/69 A; 219/72; 219/99
[51] **Int. Cl.²** **B23K 9/20; B23K** 11/04
[58] **Field of Search** .... 61/69 R, 69 A; 219/74, 219/72, 98, 99

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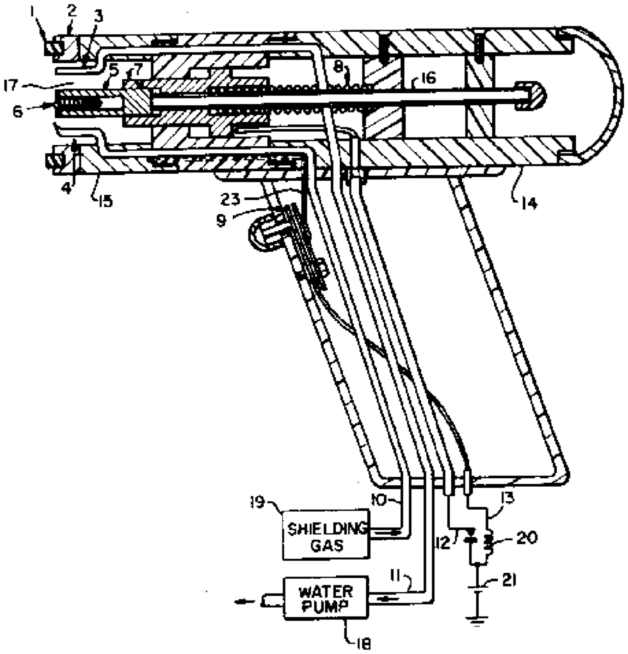
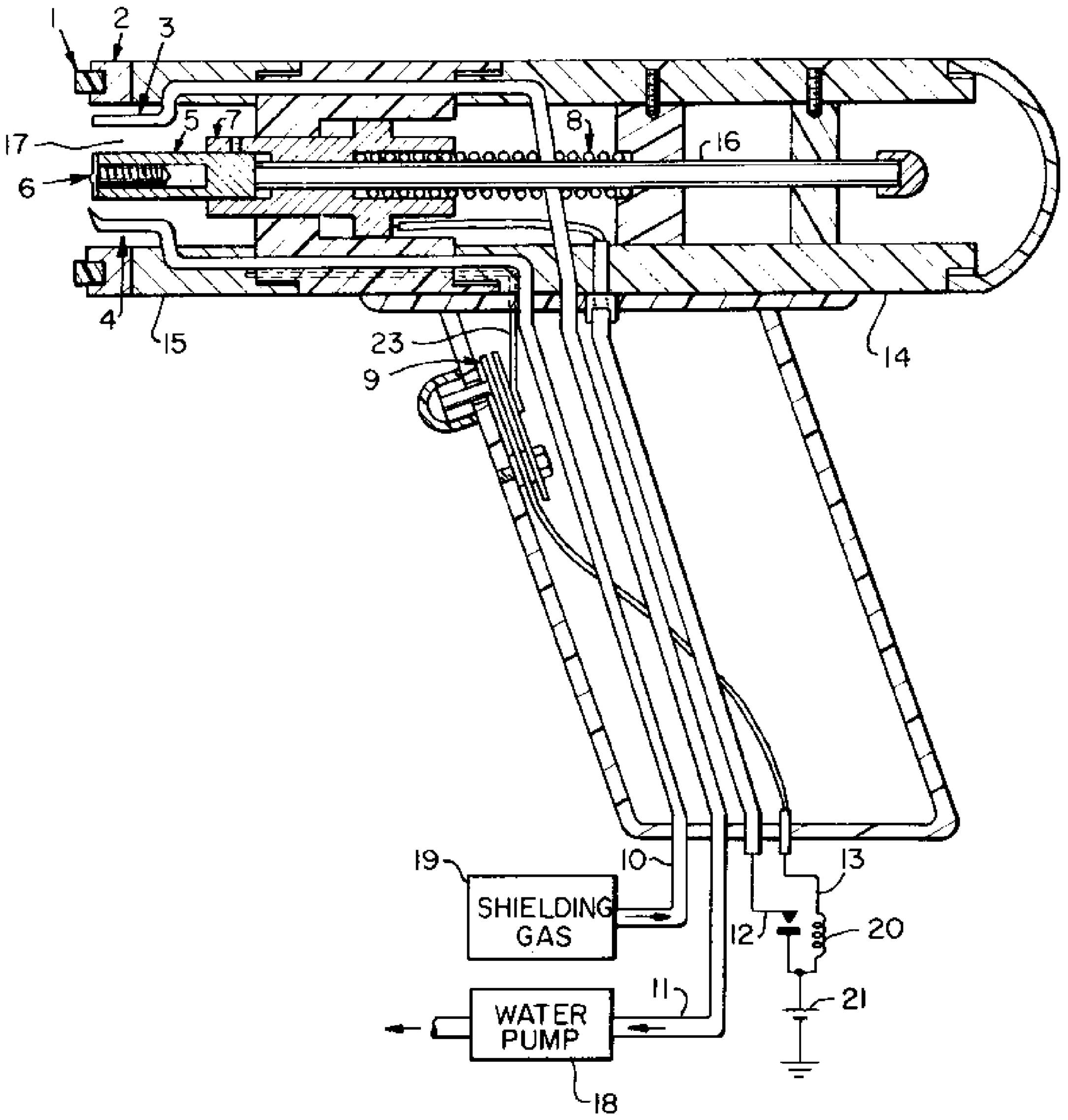
Primary Examiner—J. V. Truhe
Assistant Examiner—N. D. Herkamp
Attorney, Agent, or Firm—Arthur A. Smith, Jr.; Martin M. Santa; Robert Shaw

[57] **ABSTRACT**

A conventional stud-welding gun has been modified to allow it to be used for welding under water. The stud is contained within a water-tight enclosure formed at the end of the gun by pressing the seal at the end against the object to which the stud is to be welded. A water pump evacuates the enclosure and a stream of inert gas is provided to expel water and dry the region where the weld is to occur.

3 Claims, 1 Drawing Figure

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SHIELDING GAS
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WATER PUMP
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UNDERWATER STUD WELDING GUN

The Government has rights in this invention pursuant to Sea Grant No. 04-4-158 awarded by the National Oceanic and Atmospheric Administration in the U.S. Department of Commerce.

The general purpose of this invention is to provide a stud-welding device which can be used quickly and safely under water to join metals by means of a local pumping system with appropriate sealing materials and a clamping magnet.

The former underwater joining processes are classified as dry chamber underwater arc welding processes and wet underwater arc welding processes. These methods, however, cannot be used to join metals in the deep sea. Furthermore, the properties of welds obtained in shallow sea are not always sound. For instance, in wet underwater welding processes used at the depth that a diver can go down, the moisture surrounding the arc goes into the weld to stay and a brittleness of weldments occur.

On the other hand, in the prior-art dry chamber underwater welding processes, a large chamber is sunk; and high pressure argon or helium gas is used to obtain a dry space under the water. In this way a good weldment is obtained because the water near the point to be welded is removed. However, this facility is not feasible for use in the deep sea, because a man must dive into the dry chamber to weld. Moreover, there is no satisfactory sealing system.

It is therefore an object of the present invention to provide a new, small underwater stud-welding gun as shown in the FIGURE. By means of this gun, the inventors have made it possible to pump out the water near the welded point and to dry up the welded surface by fitting a gas nozzle near the welding chip.

With the invention of the new underwater stud-welding gun, a new technique for welding a bolt within one minute has been developed for use at deep sea levels (up to a depth of approximately 5,000 feet). This new underwater stud-welding gun can be affixed to the manipulator of very deep marine vehicles thus making possible the welding of metals at deep sea level.

The FIGURE shows a cross-sectional view of the welding gun of this invention.

DETAILED DESCRIPTION OF THE INVENTION

The preferred embodiment of the invention utilizes a modified form of a conventional stud-welding gun, as for example, a "Nelson" stud-welder. The conventional stud-welder comprises a housing **14** of plastic or similar electrically-insulating, impact-resistant material having at one end a hollow, metallic cylinder **15**. The stud **6** to be welded to a plate (not shown) is slidably contained within metallic tip **5**. The tip **5** is mounted in metallic tip holder **7** which is attached to guide rod **16**. Spring **8** mounted along rod **16** provides a compression force on stud **6** when the stud **6** is pressed against the surface to which it is to be welded.

The cylindrical end **15** has been modified to include a cylindrical magnet **2** attached to it in order to provide a magnetic attraction force to the metal to which the stud **6** is to be welded. A resilient sealing material, such as rubber, synthetic rubber or deformable plastic, is inserted in a cylindrical groove in the magnet **2**. The stud **6** extends out of the enclosure or cavity **17** formed

by magnet **2** and end **15** before spring **8** is compressed. The FIGURE shows stud **6** in the position that it will be in when welding takes place. The mechanical contact of magnet **2** with the sheet to be welded provides a stop which determines the maximum movement of the stud **6** and thereby the maximum compression of spring **8**. The seal **1** is compressed to provide a watertight chamber **17** when the stud **6** is pressed against the sheet.

A nozzle **3** contained in chamber **17** drains water from the sealed enclosure **17** through the action of water pump **18** to which it is connected by tube **11**. A nozzle **4** has its open end located in proximity to the end of stud **6**, when stud **6** is in the position shown in the FIGURE. A shielding gas, of argon or similar inert gas, provided by source **19**, flows through tube **10** and nozzle **4** to expel any water from the space between the welding surface of stud **6** and the sheet to which it is to be welded and to dry this space.

Welding is accomplished as in the conventional stud-welding gun by closing switch **9** of wire **13**. This switch **9** activates a control circuit, shown as relay **20**, by energizing the coil of the relay **20** through an electrical power source **21**. The high-current-capacity contacts of relay **20** provide the welding current from source **21** through wire **12** to stud **6**. The sheet to which the stud is to be welded is connected to the ground terminal of power source **21**. Switch **9**, as shown, is connected to the metallic cylindrical end **15** and magnet **4** by wire **23**. Therefore, the magnet **2** must be in electrical contact with the sheet to be welded before the relay **20** can be activated and thus provides a safety feature.

Although the preferred embodiment of the invention has employed a magnet **2** to assist the operator in holding the end of the gun in contact with the sheet to be welded, it is apparent that the magnet **2** is not absolutely necessary. If magnet **2** is not used, the cylinder **15** would be longitudinally extended so that it occupied the region of the magnet **2**. Other variations of this invention will be apparent to those skilled in the art without departing from the scope of this invention.

What is claimed is:

1. An underwater stud-welding gun comprising

a stud-welding gun having a cylindrical end enclosure containing a stud-holding tip,

a resilient sealing member attached to the end of said cylindrical enclosure and extending along the circumference of said cylindrical enclosure,

means for removing water from said cylindrical enclosure when said sealing member is pressed against a welding surface thereby forming a watertight sealed cylindrical enclosure,

means for providing a flow of inert gas in the space between the end of the stud-holding tip and said surface to remove any remaining water from said space.

2. The stud-welding gun of claim **1**, comprising, in addition,

a magnetic member attached to the end of said cylindrical enclosure to provide an attraction force between said cylindrical enclosure and said welding surface, said force acting to compress said sealing member and thereby assist in providing the sealing of said cylindrical enclosure.

3. The apparatus of claim **1** wherein said inert gas is argon.

* * * * *

United States Patent [19]
Masubuchi et al.

[11] **4,069,408**
[45] **Jan. 17, 1978**

[54] METHOD AND APPARATUS FOR UNDERWATER SUBMERGED ARC WELDING

[75] Inventors: **Koichi Masubuchi**, Arlington; **Chon-Liang Tsai**, Cambridge, both of Mass.

[73] Assignee: **Massachusetts Institute of Technology**, Cambridge, Mass.

[21] Appl. No.: **693,576**

[22] Filed: **June 7, 1976**

[51] **Int. Cl.**^{2} **B23K 9/18**
[52] **U.S. Cl.** .... **219/72**; 219/73 R; 219/73 A
[58] **Field of Search** .... 219/72, 73 R, 73 A

[56] **References Cited**

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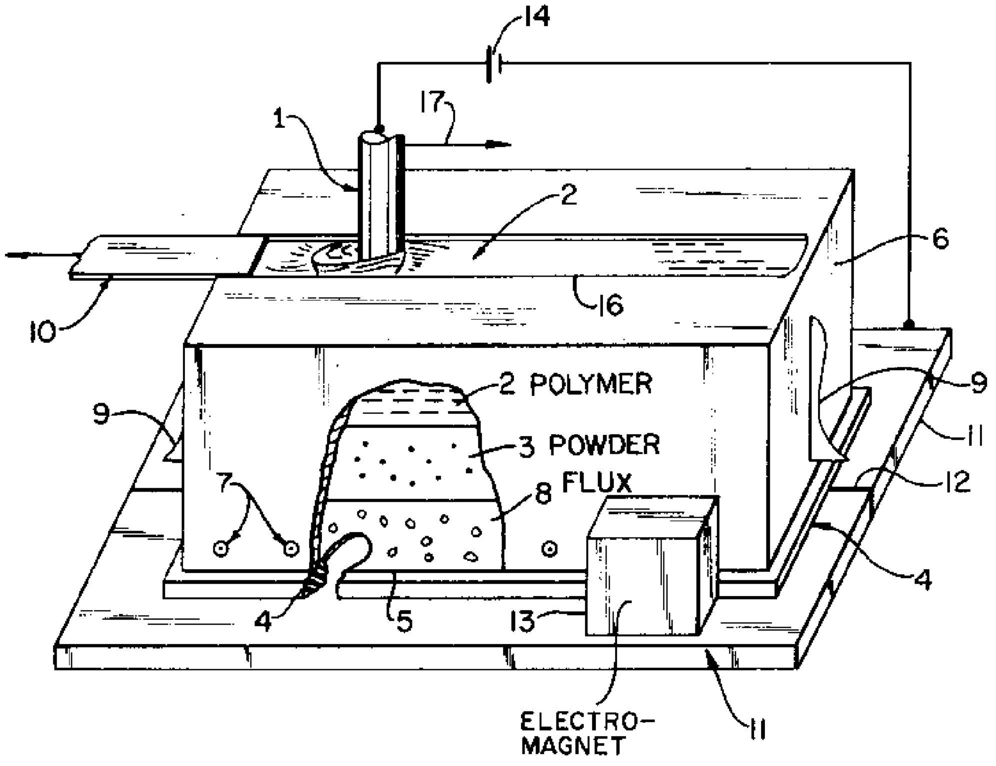
Primary Examiner—Elliot A. Goldberg
Attorney, Agent, or Firm—Arthur A. Smith, Jr.; Martin M. Santa; Robert Shaw

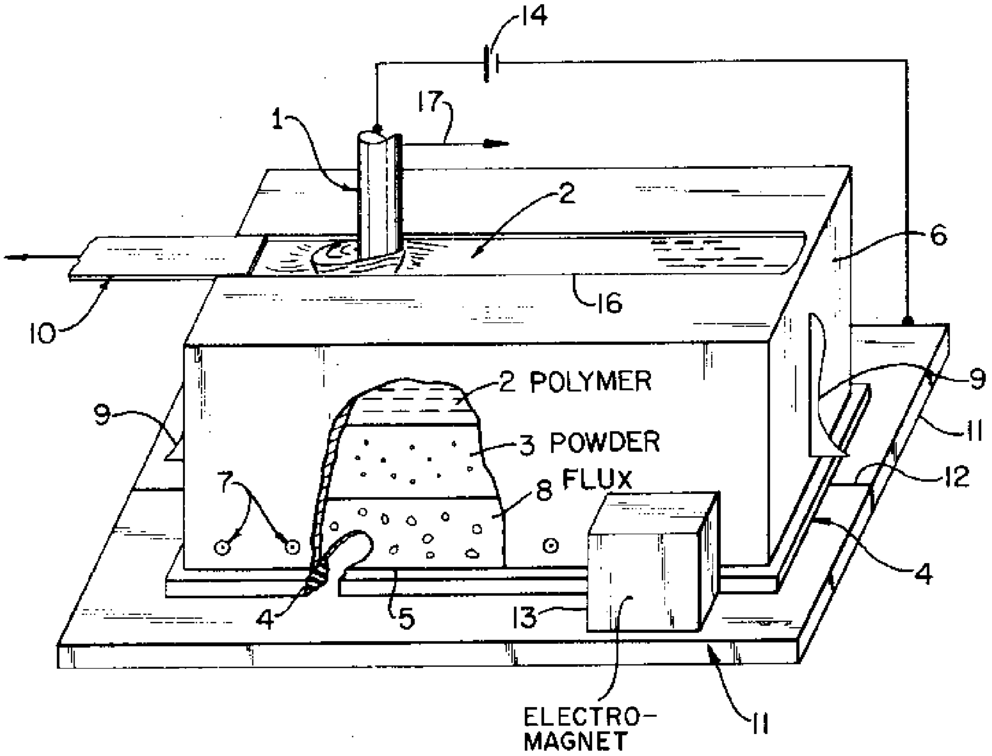
[57] **ABSTRACT**

According to the method and apparatus of this invention, water is kept away from the arc in underwater arc welding by means of material contained in a water-tight enclosure. The water-tight enclosure is formed by pressing the seal at the bottom of the enclosure against the object to be welded and by closing the opening for the electrode on top of the enclosure by using the fluid nature of a viscous polymer. Gas generated in the enclosure during welding is expelled through check valves located along two longitudinal sides of the enclosure.

The enclosure is prepared above the water surface and then delivered to the welding site. No inert gas is needed.

12 Claims, 1 Drawing Figure




14
17
1
2
6
16
10
9
2 POLYMER
3 POWDER
FLUX
8
7
12
11
4
5
13
ELECTRO-
MAGNET

METHOD AND APPARATUS FOR UNDERWATER SUBMERGED ARC WELDING

BACKGROUND AND SUMMARY OF THE INVENTION

The Government has rights in this invention pursuant to Grant No. 04-6-158-44007 awarded by the National Oceanographic Atmospheric Administration, Sea Grant and has reserved rights as set forth in Section 1(*f*) and 1(*g*) of the Oct. 10, 1963, Presidential Statement of Government Patent Policy.

The invention relates to underwater submerged arc welding, which is an electric welding process in which a consumable electrode is fed into a weld zone at a controlled rate while a continuous blanket of molten flux shields the weld zone from contamination. More particularly, this invention has as an object the provision of a device and method which enables the utilization of a submerged arc welding process underwater. More particularly, the invention provides a device which eliminates water contact in the arc area during underwater welding and hence reduces greatly the rapid cooling experienced in the conventional underwater welding processes. This feature together with other objects and features such as the absence of the need for water-displacing gases, the absence of water-current effect, and minimum hydrogen content in the arc area will become apparent from the detailed description of the invention.

The quality of welds made with conventional underwater wet welding processes is usually not sound. The moisture surrounding the arc goes into the weld and embrittles the weld. The rapid cooling due to water bubbling because of concentrated arc heat induces martensitic structure in heat affected zone of the weld. Code quality cannot be achieved. On the other hand, dry chamber quality underwater welding process is not economically feasible, although a sound weld can be produced with this technique.

It is therefore a general object of the present invention to provide an improved underwater welding method and apparatus. By means of the method and apparatus of this invention, the inventors have made it possible to keep water away from the weld area and maintain a continuous slag covering on the weld head throughout the welding period. Code quality can therefore be achieved.

The FIGURE shows a partial cross section of the apparatus of this invention.

DETAILED DESCRIPTION OF THE INVENTION

A flux-stuffed enclosure **6** is prepared with three layers of chemicals. At the bottom of the enclosure, layer **8** is conventional welding flux which provides a continuous protective environment during welding. A layer of powder insulation material **3** above layer **8**, such as limestone powder, is able to withstand high temperature, is an electrical insulator, and provides a drying agent which absorbs any water moisture which penetrates through sealing layer **3** because of electrode **1** motion during welding. The thermally insulating material **2** also retains heat in the enclosure **6** to give a tempering effect on the bead behind the arc produced during welding. The top sealing layer **2** is used to prevent water from penetrating into the layers **3**, **8**. It has been found that a water insoluble, high viscosity polymer such as Polybutene No. 24 by Chevron having a viscosity of 1000 SFU at 210° F, functions well as a water seal for the moving electrode when welding is occurring.

The bottom sheet **5** of the enclosure **6** comprises a sheet of metal or plastic which is attached to the side walls of the enclosure. The bottom sheet **5** holds the layers, **2**, **3** and **8** in the enclosure and prevents water from wetting the flux **8** which is contiguous to the bottom sheet **5**. The bottom sheet **5** may be made of very thin steel, aluminum foil or other electrically conductive material of sufficient strength to contain the contents of the enclosure. Its thickness should also be such that when electrode **1** which has penetrated layers **2**, **3** and **8** and is electrically energized by source **14** touches sheet **5** the arc produced melts the sheet **5** and also the electrode **1**, the base metal **11**, and the flux **8** into a common pool. The molten flux acts as a cleaning agent and floats to the top of the weld to form a protective slag while the weld solidifies as in conventional welding.

Alternatively, a thin plastic or other electrical nonconductor which is easily penetrated by the welding electrode may be used as the bottom sheet **5**, in which case the arc occurs between electrode **1** and metal **11** as in conventional welding.

Gases formed by chemical reaction of the flux due to welding heat are expelled through check valves **7** located along two longitudinal sides when pressure is higher than the ambient pressure. Welding is therefore performed under a completely protected environment.

After the layer-filled enclosure **6** is delivered to the welding site by a driver or other means, the slot **16** of the enclosure is aligned with the joint **12** of the plates **11** to be welded by means of alignment guides **9**. The bottom sheet **5** of enclosure **6** is pressed against plates **11** to displace most or all of the water between sheet **5** and plates **11**. A slight outward bulge in sheet **5** before pressing is desirable for this purpose. A resilient sealing member **4** of rubber, plastic or other suitable material, on the bottom sheet **5** preferably near its periphery, provides a water seal when the enclosure **6** is in place. A suitable clamping device such as electromagnet **13** may hold enclosure **6** in place during the welding process. Other mechanical means or manual pressure could be used for holding enclosure **6** in place.

The enclosure **6** has a slidable cover **10** which retains the contents of the enclosure **6** after it has been prepared with its layers of material and during the period that it is underwater and being delivered to the welding site. The cover **10** is removed before welding is to take place, after the enclosure has been placed over the joint with the slot. Alternatively, the cover **10** may be pushed along by the electrode **1** during the weldig process. Also, another alternative is to have the cover **10** made of a thin tearable material, such as plastic, which is perforated by electrode **1** at the commencement of welding and is further torn as the electrode is moved along the slot **16**. The cover **10** may be dispensed with if the filled enclosure **6** is maintained relatively level for all but short periods of time, which are insufficient for significant flow of sealing layer **2** material out of enclosure **6**.

The process of welding after the enclosure **6** has been clamped to the metal to be welded is simple. The energized electrode is inserted into the enclosure **6** through the layers **2**, **3** and **8** at one end of the slot **16**. After the welding arc occurs, the electrode is moved along the slot at the proper rate to achieve a good weld bead. The viscous fluid layer **2** at the top of the enclosure closes around the electrode **1** moving in direction **17** sufficiently rapidly to prevent substantial amounts of water from penetrating layer **2** to be absorbed by layer **3**. The electrode **1** and enclosure **6** are removed at the completion of the weld.

While the particular embodiment of the invention specifically discussed above seems preferable at the present time, modification thereto may occur to those skilled in the art without departing from the spirit and scope of the invention. Hence, the invention is not to be construed as limited to the particular embodiment shown and described herein, except as defined by the appended claims.

What is claimed is:

1. Apparatus for underwater arc welding comprising:
   an enclosure having a perforable bottom,
   said enclosure containing layers of welding flux, an insulating powder and a water-insoluble, high-viscosity liquid in that order on said bottom,
   a longitudinal slot in the top of said enclosure
   whereby an electrode may enter said enclosure through said slot to penetrate said layers to perforate said bottom.

2. The apparatus of claim **1** comprising in addition
   a resilient sealing member attached to the bottom of said enclosure.

3. The apparatus of claim **1** wherein said perforable bottom is a thin metallic sheet capable of being perforated by the arc produced by electrode when energized.

4. The apparatus of claim **1** wherein said perforable bottom is a thin non-metallic sheet capable of being perforated by contact with the electrode.

5. The apparatus of claim **1** wherein said liquid is a polymer.

6. The apparatus of claim **1** comprising in addition
   a slidable cover to cover the slot in the enclosure and capable of sliding along said slot in response to movement of the electrode.

7. The apparatus of claim **1** comprising in addition
   a cover for said slot capable of being perforated by said electrode and being torn by said electrode as it moves along the slot.

8. The apparatus of claim **1** comprising in addition
   means for expelling gas from said enclosure generated during the welding process.

9. The apparatus of claim **8** where said means comprises
   check valves located along the longitudinal side of the enclosure.

10. The apparatus of claim **1** comprising in addition
    means for holding the bottom of the enclosure in mechanical contact with the metal to be welded.

11. The apparatus of claim **10** wherein said holding means is an electromagnet.

12. A method for underwater arc welding joints in metal pieces comprising
    preparing out of water an enclosure having a perforable bottom,
    said enclosure containing layers of welding flux, an insulating powder and a water-insoluble, high-viscosity liquid in that order on said bottom,
    a longitudinal slot in the top of said enclosure to allow an electrode to enter said enclosure through said slot to penetrate said layers to perforate said bottom,
    placing said enclosure in contact with the metal to be welded with its slot over and along the joint to be welded,
    inserting an energized electrode through said slot to make electrical contact with said metal to form an arc,
    moving said electrode along said slot while maintaining said arc to produce a weld along said joint,
    said enclosure and metal being underwater during said welding.

* * * * *

APPENDIX B

SURVEY ON DEPTH-RELATED TECHNICAL PROBLEMS OF CURRENT JOINING PROCESSES

Chapter 4 Depth-Related Technical Problems of A.P. Moore's Thesis Entitled "Metals Joining in Deep Ocean".

As operating depths are increased, the effects of pressure on joining processes become of far greater importance. Although a certain amount of work on this topic has been done, a great deal more must be completed if greater joining depths are to be achieved. In this chapter, technical problems anticipated in extending the depth capacity of those techniques outlined in Table B-1 is reviewed. An assessment of possible corrective measures as well as an identification of practical future developmental work is made.

Many of the arc-welding processes which appear in Table B-1 are subject to the same depth-related problems due to the characteristics of the underwater arc itself. These common problems will be dealt with first. Following this, the other processes noted in Table B-1 will be examined in order to define technical problems which must be solved in expanding operational depth limits.

B.1 Electric Arc Processes

A welding arc is a sustained electrical discharge through a high temperature, high conductivity column of plasma. It is produced by a relatively large current, in the neighborhood of 200 amperes, and a low voltage of from 35 to 50 volts. The plasma, through which electrical conduction takes place, contains a radiating mixture of free electrons, positive ions and some highly excited neutral atoms. The electrons drift toward the anode and the ions toward the cathodes. Electromagnetic forces constricting the arc determine this drift velocity. Since the majority of the arc power (75 to 90 percent) is delivered to the anode, the workpiece is most often made the anode and the electrode the cathode in underwater welding. Termed straight polarity, this arrangement takes advantage of the high density, high velocity, electron bombardment of the anode for heating [54].

In addition to electromagnetic forces, an underwater arc column is compressed by hydrostatic forces and cooling effects. These hydrostatic forces are, of course, a function of depth. Cooling effects are caused

Table B-1

Joining processes with potential for deep ocean application

Process	Possible Deep Ocean Application
I. Processes Suitable for General Repair and Fabrication	
Wet shielded metal arc	
single-pass	temporary repair; padeye attachment
multi-pass	platform, habitat, pipeline repair possible underwater fabrication
hyperbaric chamber (enclosing diver and work)	pipeline repair and hot-tap work fabrication of deep pipelines
small fixed or movable chamber (enclosing only work)	platform and other repair work
shrouded metal arc	presently under development
wet plasma arc	
wet gas metal arc	
mechanical joining techniques	platform, submerged production system, pipeline repair
II. Processes Suitable Primarily for Establishing Attachment Points	
exothermic welding/brazing	attachment point; possible pipeline repair
explosive welding	attachment point
velocity power tool	attachment point

by the surrounding water as well as by hydrogen dissociated from the steam in the welding bubble. Further, the arc may be geometrically constricted by the cathode spot or electrode in straight polarity welding [10]. All of these forces combine to increase the rate of collision among electrons, ions, and neutral particles, causing a high pressure region. Also, in order to continue the mechanism of current transfer, the conduction cross section must be maintained. Therefore, if conducting forces restrict the arc area, the core temperature must increase to maintain the current. Core temperatures can range from 5000 to 50,000°K depending on the degree of ionization and arc constriction [54].

The special characteristics of an underwater arc create a number of depth-related effects which must be considered in the development of any electric arc joining process for the deep sea. These effects are discussed in the following sections.

B.1.1 Penetration and Weld Bead Shape

The very high arc core temperatures found at greater depths greatly increase arc penetration. This can have both beneficial and detrimental effects. Increased penetration, accompanied by more rapid metal transfer, can lead to higher, more efficient deposition rates. On the other hand, at the high pressures found on the deep ocean floor, increased penetration can lead to burnthrough [54].

In laboratory research, Madatov reported an increase in penetration with depth for shielded metal arc (SMA) welds, as well as widening of the penetration shape factor (W/P) from 5 to 3 [40]. De Saw et al. found that reverse polarity SMA welds were shallower, wider and less porous than straight polarity welds [18]. This reversal of arc characteristics at depth was not explained. However, during extensive commercial repair work at sea, Grubbs has noted that excessive penetration is not a problem in multipass SMA welding, even at depths in excess of 200 feet [26].

SMA weld bead characteristics have been found to be quite satisfactory in actual service when the sophisticated multipass technique is employed. Developmental work in extending the depth capability of this process centers around electrode coatings and has resulted in the development of satisfactory electrodes for low carbon steel (carbon equivalent less than 0.4) welding in depths exceeding 200 feet. At present, austenitic electrodes may be satisfactorily employed for steels with higher carbon equivalents in depths up to 800 feet and work is underway to extend this capacity to over 300 feet [25].

A number of investigators have studied the effects of pressure on the gas metal arc (GMA) welding process. Pilia found that welds made at 60 feet were peaked and thin and that burnthrough was a problem at 80-100 feet because of excessive penetration [10]. In dry welds made under pressure on aluminum, Brandon noted that the weld cross sectional area, the weld depth to width ratio and penetration all increased with increased pressure. Careful control of filler metal feed speed was the single most important factor available to offset or control these effects. Arc voltage and welding travel speed were less influential in their effects on weld penetration and shape [9]. In underwater chamber welding, the diver-welder must manipulate the arc differently than in surface welding in order to offset the more narrowly concentrated heat of the constricted arc. It is more difficult to initiate the arc, to maintain a stable arc and to obtain good fusion across the width of the weld joint. The welding arc becomes more intense and the electrode wire melts at a faster rate as the pressure increases. This causes a larger weld pool and control difficulties, and can lead to such weld defects as overlap and improper fusion [45].

As welding pressure increases, the only significant change in the characteristics of a gas tungsten arc (GTA) is a constriction of the arc column leading to an increase in arc voltage. This causes an effect not unlike that of a plasma arc weld and results in greater weld bead penetration, often as much as 50 percent at 20 bar [36].

B.1.2 Current and Voltage

Compressive forces acting on the underwater arc make voltage-amperage curves concave or rising. Thus, though the voltage needed to strike the arc is higher than the voltage needed to maintain it, the amperage grows as the voltage decreases once the arc has been established. As depths increase and greater constriction due to water pressure is experienced, the current density continues to increase [10]. At great depths, Madatov found the large concentration of heat from the increased current density acted to limit welding currents to 180-240 amps [40].

Although, at one time, apparent increases in current requirements for SMA welding were attributed to heat losses through thermal conduction [30], it is now believed by some researchers that increased current demands are primarily due to the constriction of the arc and increased resistance heating of the rod as greater pressures are encountered [54]. Arc length must also be considered, since longer arc lengths result in greater hydrogen cooling and hydrostatic effects, which combine to cause greater constriction and current density. To compensate for these factors, it has been suggested that the welding current be increased by 10 percent per atmosphere of additional pressure in order to maintain similar arc conditions [7]. This suggestion has not been confirmed by practical experience, however. During multipass SMA repair welding at various depths up to and exceeding 200 feet, Grubbs has found no need to increase current drastically with depth. He has found that it is necessary to increase current approximately 10 percent over that required for air welds and to increase current as cable length is increased but has noted that there is no need for a current increase with depth [25].

Several reports have been issued on the effects of pressure on the GMA welding process [8,9,12,48,51]. From them, much information concerning the effects of depth upon current and voltage can be gained.

Arc power consumption is a meaningful measure of welding performance which complements voltage and heat input data. An idea of the arc power consumed in any region can be gained by measuring the voltage consumed and remembering that the same current flows through all elements in a welding circuit. These distinct voltages, which are shown in Figure B-1, are the IR drop in the electrode stickout, the anode voltage, the positive column voltage and the cathode voltage. Since total arc voltage will be divided differently among these regions depending on welding conditions, these distinct voltages must be considered. Figure B-2 illustrates arc length vs. voltage. The IR voltage drop can be expected to remain constant and not vary with minor current variations. Extrapolating the curves to zero length eliminates the contribution to total voltage of the column voltage. These zero arc length voltages, which represent the sum of anode and cathode voltages, increase with pressure by differing amounts as shown by the varying slopes of the constant pressure curves [48]. Similar results were reported for underwater arcs by Avilov in earlier work [7].

This increase is probably due to anode voltage, as can be explained by using the following formula for direct current reverse polarity melting rate [48]:

$$M = aI + bLI^2$$

where: a is a constant dependent upon anode size and material

b is a constant dependent on electrode diameter and resistivity

L is the electrode stickout distance

The first term on the right represents the anode melting contribution and the second, resistance melting. In this equation, the electrode voltage drop is independent of the temperature at the end of the electrode. Experimentally, more current is required to maintain the melting rate than would be predicted by the melting rate equation. Since no change can be expected in the resistance heating term, the anode melting term must increase. This conclusion is supported by Maecker's analysis of plasma jets.

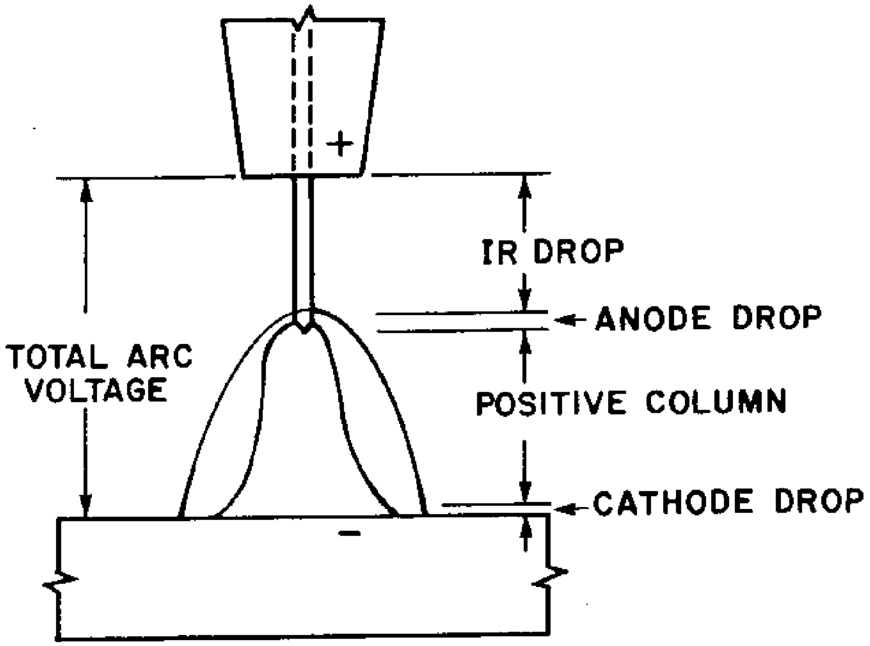


FIGURE B-1 Arc voltage division[48]

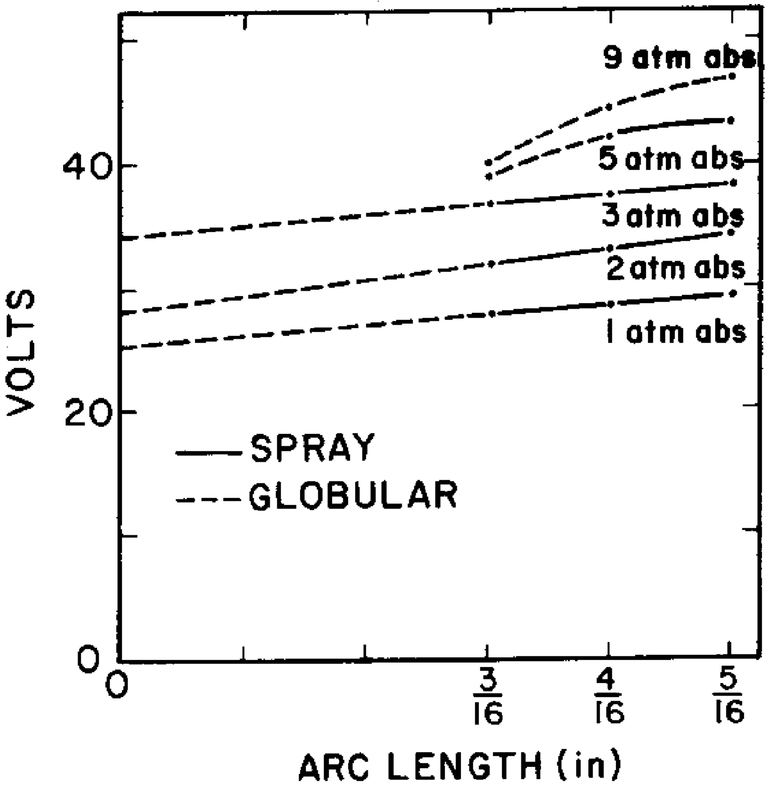


FIGURE B-2 Arc length vs. voltage(48]

Entrained cold gas has to flow over the electrode to be heated and accelerated. This energy requirement should result in an increase in the anode voltage drop with pressure [48].

Figure B-3 presents voltage and pressure data for the same arc length values in a different manner. Figure B-4 is the power vs pressure relation calculated from measurements of arc voltage [48].

Brandon, in his report, noted that increased pressure is detrimental to arc stability, but that increased voltage promotes stability. At low pressures, near atmospheric, arc stability is relatively insensitive to voltage, but at high pressures, increased voltage greatly increased stability. This acts to reinforce previous work which suggests that increasing voltage when ambient pressure rises may be a useful technique[9].

Several experimentors discovered that constant potential power sources were not adequate for work at higher pressures. Drooping power sources were used at pressures greater than about 8 bar to provide the necessary open circuit voltage for high pressure welds [12,48].

In summarizing current and voltage relations found in welding under pressure, the following points should be noted:

1. As hydrostatic pressure adds to electromagnetic and cooling constricting forces, the current density increases and a higher voltage is required to maintain a constant arc length.
2. Power requirements increase with depth.
3. Current requirements may increase somewhat with depth but the magnitude of this increase is in question.

Further work is needed to clear up areas where confusion exists as well as to verify previous work. Whenever possible, such work should be undertaken in an actual ocean environment, over a wide range of actual undersea projects. Results which appear to be significant in laboratory tests conducted under carefully controlled conditions are often not important factors in actual marine work.

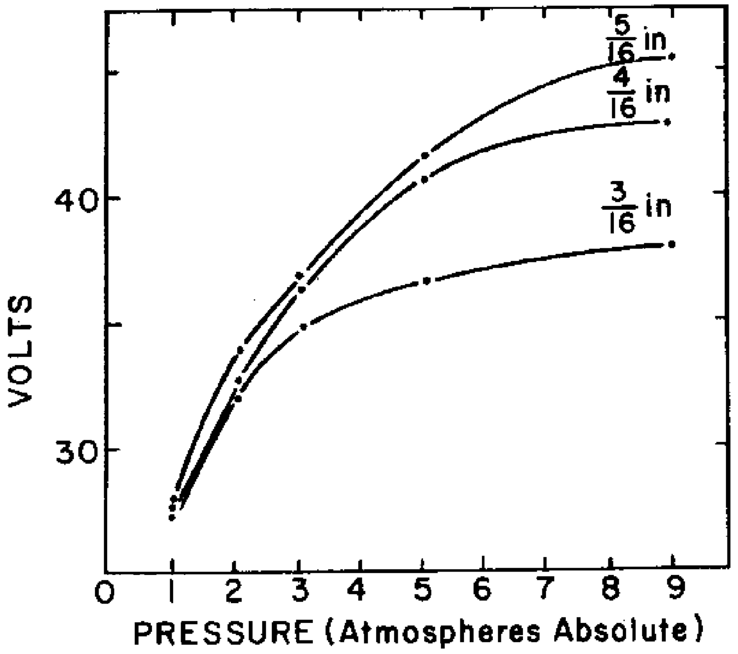


FIGURE B-3 Arc voltage vs. pressure [48]

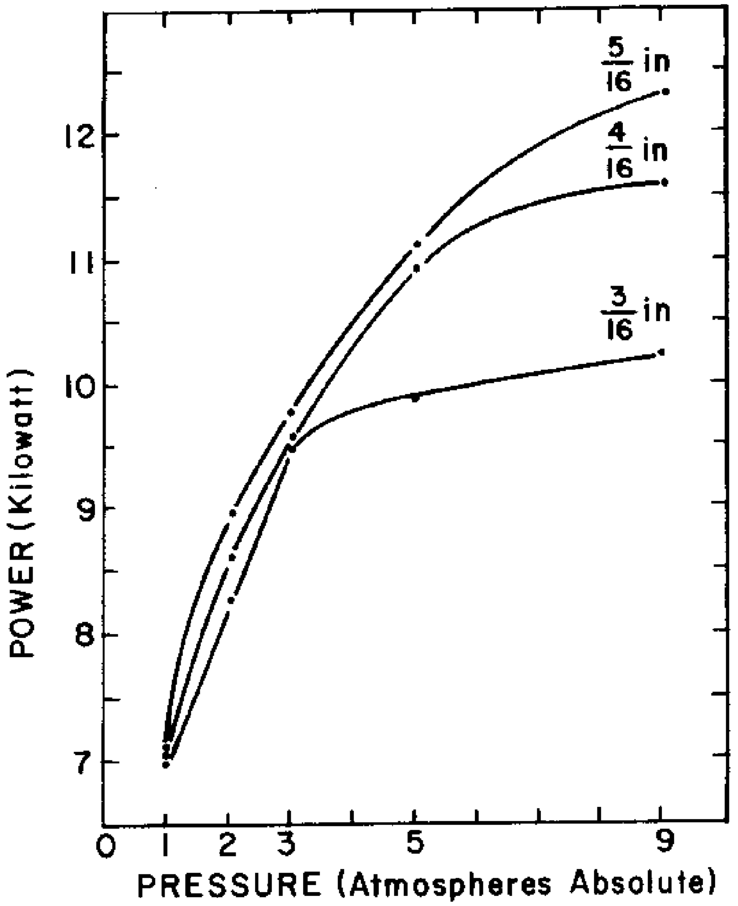


FIGURE B-4 Arc Power vs. pressure [48]

B.1.3 Metal Transfer

There are three basic modes by which metal from the electrode can be transferred across to the weld pool. The one which occurs at the lowest current level is dip or short circuit transfer. In this mode, electrode feed rate, current, and power source dynamics are such that the metal transfers across during the short circuit and, in the remainder of the cycle, the arc is maintained without metal transfer. As the current is increased, other parameters remaining the same, the transfer mode shifts to globular or drop transfer and the metal is transferred in large drops that travel slowly to the workpiece. This shift occurs because the ohmic heating of the electrode and the anodic heat developed at the tip generate enough heat to permit large globules of metal to detach without short circuiting. As current is increased further, rapid melting of the electrode occurs and droplets are ejected as a fine stream or spray by the action of plasma jets. In globular transfer, gravity is the dominant force, in spray transfer, the strength of the plasma jets is dominant. These modes may undergo transformations from one to another as parameters are altered or may occur in combination [12].

Maecker's plasma jet theory is useful in explaining the effects of pressure upon transfer in the spray mode. As the arc is constricted, radial pressures increase. Pressure equalization causes a flow along the axis toward larger cross sections and lower current densities. This flow draws cold gases into the arc and further constricts the discharge cross-section at the electrode, increasing the pumping action. This process continues until the temperature gradient becomes steep enough for a steady state to exist. The steady plasma jet attracts current paths by its good conductivity. These paths supply enough joule heat to offset the conductive cooling of the plasma jet and the balance is maintained[48].

As ambient pressure rises, the thermal conductivity of the gases increases. This increased conductivity causes a constriction of the arc and a new, higher velocity steady state is attained. This results in an increased drop transfer rate and deeper penetration, up to a certain level.

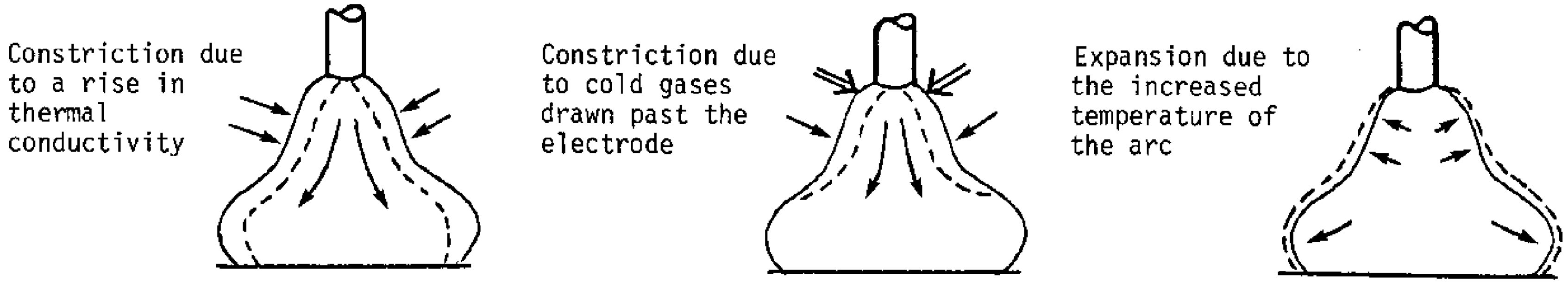
At sufficiently high pressure levels the combined effects of the reflected vapor jet from the workpiece and a pressure induced squeeze effect on the bottom of the arc column begin to retard the plasma flow rate. This causes an eventual reversion to globular transfer [48]. Figure B-5 illustrates the balance between arc plasma and hydrostatic forces [10].

In studies of the effects of pressure on the GMA process, Billy and Perlman et al. found that a reversion from spray to globular transfer occurred at sufficiently high temperatures. The arc also became unstable resulting in an excessive amount of metal vapor and spatter as well as an uncontrollably large weld puddle. Poor, highly crowned weld beads were also formed after reversion to globular transfer [10,36,48]. Burrill and Levin also found that there was a marked trend toward decreased metal deposition efficiency due to metal vapor formation and spatter. However, they could not confirm a change in the mode of transfer to globular. This may have been due to their use of a higher voltage power source [12,36].

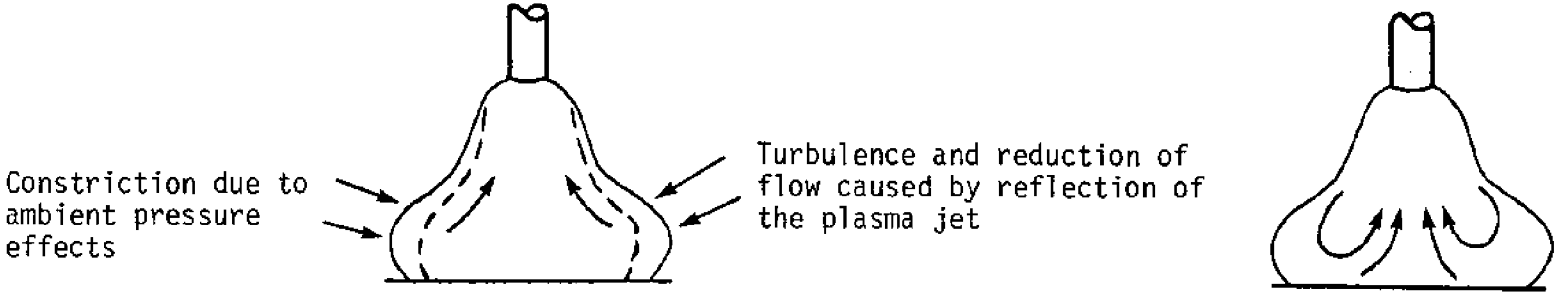
Figure B-6 illustrates the increase of spray transition current and voltage with rising pressure for a GMA process [48].

With the GTA process, arc instability does not arise since the wire is not part of the arc system but is fed and melted directly in the weld pool. The only significant change in the GTA arc with increased pressure is a constriction of the arc column which leads to an increase in arc voltage and penetration. At higher pressures the GTA weld is similar to one made by the plasma-arc process. The increased penetration may make it possible to increase welding speed slightly thus improving this process' chief shortcoming [36,45].

The normal metal transfer mode for SMA welding using the drag or touch method is small droplets, except for an occasional arc short circuit due to the formation of a large drop. Silva found that, even at shallow depths, SMA welding underwater resulted in globular rather than spray transfer[10]. Madatov found that the time taken to form a drop on the electrode and the time that the drop spends in the arc bubble atmosphere



A. Forces acting on the top of the arc. The net result of these forces is a tendency for accelerated metal transfer and increased penetration.



B. Forces acting on the bottom of the arc. The net result of these forces is a resistance to metal transfer and decreased penetration.

Forces A and B must be in equilibrium. When forces A predominate metal transfer is in the spray mode. As forces B become larger, the plasma jet is decreased until drop transfer replaces spray transfer.

FIGURE B -5 The effects of depth on arc characteristics

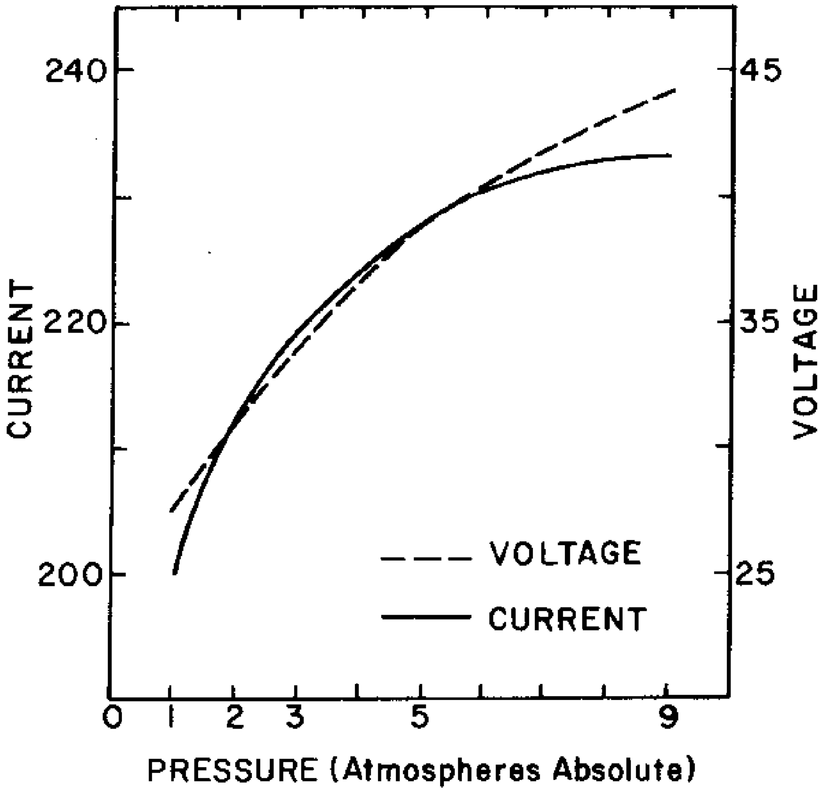


FIGURE B-6 Spray transition with changing pressure

were about the same for the SMA process. This is in contrast to thin wire welding processes in which the time spent in the bubble atmosphere often exceeds the time spent in drop formation. Madatov found that SMA drops transferred at a rate of 44 per second during his experiments [10].

In summary, increased pressure on the welding arc results in arc instability and a tendency to revert from spray to globular transfer. Increasing the voltage acts to prevent the revision to globular transfer, but does not prevent arc instability and the resultant loss of deposition efficiency due to spatter and vaporization. One suggested solution to this quandary is to employ lower heat input versions of the GMA process such as dip-transfer and the pulsed-arc technique [45]. In the dip or short circuit mode, the filler wire first shorts out to the molten weld pool. Next, the current surges and the filler wire is melted off and the arc reestablished. These shorts occur 50-70 times a second with metal transfer taking place during each short. In pulsed-arc welding, the reverse effect occurs. The filler wire melted by the arc is projected across the arc by the current which is pulsed at 60 times per second. Both of these processes involve heat inputs 20-30 percent lower than conventional GMA welding [45].

A great deal of work has been done studying the mechanism of metal transfer in arc processes under pressure. It appears that many of the original questions in this field have been answered and the major problems isolated. Much work remains to be done, however, in solving these problems.

B.1.4 Bubble Dynamics and Shielding Gas

No results have been reported on the effects of depth on gas evolution rates. It has been suggested that this is an area that requires work in the future [55].

The effects of increased pressure upon the weld bubble are fairly easy to determine by assuming that the bubble atmosphere is an ideal gas. Since the bubble atmosphere is predominantly hydrogen this assumption is acceptable for pressures and temperatures of practical significance. The volume of a gas bubble containing a given mass is directly proportional to gas temperature and inversely proportional to pressure:

$$V \alpha \frac{T}{P}$$

As water depth increases, the pressure term increases. Increasing hydrostatic pressure also causes greater constriction of the arc resulting in higher current densities and greater arc temperature. This raises the temperature of the gas generated. Arc temperature does not increase as steeply as pressure, however, so the pressure term dominates and the volume of the bubble decreases as greater operating depths are reached. This means that the protection afforded a SMA weld made without supplementary gas shielding will decrease.

Silva has developed relations which link the velocity and diameter of a rising bubble to its depth [55]:

$$V=\sqrt{\frac{4ghd\quad(\rho_w-\rho_b)+0.532d^2}{2\rho_b d+3C\rho_w h}}$$

$$d=\sqrt{\frac{p+\rho_w gD}{p+\rho_w gh}\cdot d_D^3}$$

where V = upward velocity (ft/sec)

g = acceleration due to gravity (ft/sec^2)

h = depth of bubble being considered (ft)

D = depth of arc (ft)

p = atmospheric pressure (lb/ft^2)

C = coefficient of drag for a sphere (dimensionless)

d, d_D = diameter of bubbles at h or D (ft)

ρ_w, ρ_b = mass density of water or bubble (slug/ft^3)

Increased pressure also affects shielding gas behavior. The density of the gas is increased and high flow rates are required. Figure B-7 illustrates the increase required by Burrill and Levin in their experiments [12]. Flow rates as great as ten times those used for surface welding have been required. Arc behavior may also change with depth and influence the selection of the shielding gas and the gas flow rate [45].

Liquification of shielding gases places a depth limit on their use, since the torch would cease to function [36]. Of the gases suitable for shielding, argon and hydrogen remain gaseous at the greatest pressures. At 0°C, argon liquifies at 3570 meters and nitrogen at 5090 meters. Heating of a gas may extend its range slightly, but practical considerations limit this action [54].

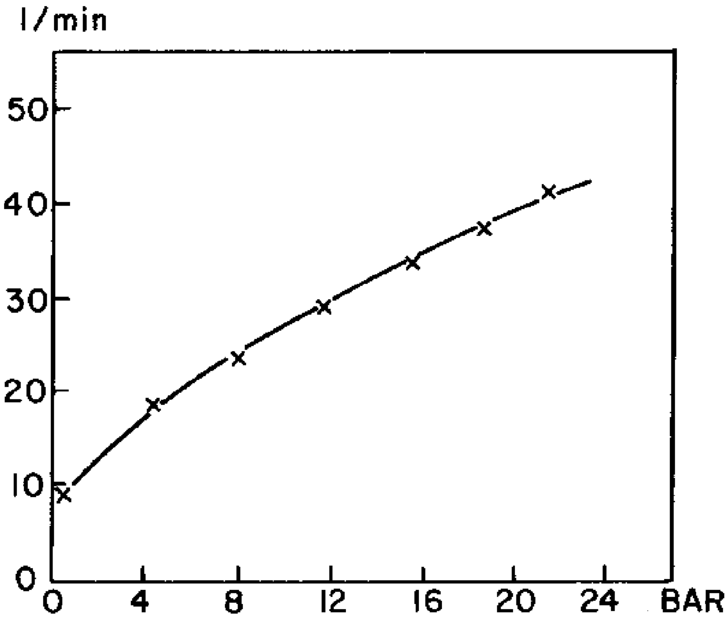


FIGURE B-7 Increase of shielding gas flow with pressure

B.1.5 Porosity and Chemical Composition

Porosity is caused by small gas bubbles becoming trapped in the weld metal. The small hole, or pore, in the welded joint is a mechanical defect and is not as serious as the chemical problem associated with the presence of the gas. Having oxygen or nitrogen present is harmful because oxides and nitrides formed from these gases cause embrittlement of the metal. The presence of hydrogen is even more critical but its effects will be considered separately in the next section [10].

Two possible causes of porosity in SMA welds made underwater have been suggested. The first, not a depth-related effect, is that porosity is associated with wet electrode coatings. Chicago Bridge and Iron welders have found that keeping electrodes dry in a special underwater case until they are actually placed in the holder results in high quality, porosity free welds [25]. Better coatings, which resist moisture penetration, also help to overcome this problem. There has been speculation that increased porosity found in SMA welds made at greater depths is related to the shrinking of the protective gas bubble under high pressures. It is thought that protection of the arc and molten weld metal normally provided by the gas bubble breaks down [45]. This problem might be solved by using a shroud to trap shielding gases generated or by the use of supplementary shielding gas.

In GMA welding tests made under pressure, porosity was found to be reduced when pressure was increased. This is believed to be due to the fact that the gas pressure in the bubbles was lower than the sum of the hydrostatic pressure of the molten metal, the surface tension of the molten metal, and the ambient pressure of the chamber [8,48]. If this is the case, chemical problems will remain unchanged since the amount of gas in the weld is not changed [51]. Brandon noted a correlation between pore size and shape and turbulent arc and puddle action in GMA pressure welding. This might become a significant problem if pressures are sufficiently great to cause the welding arc to become unstable. In his tests, Brandon found that filler metal speed rate was the only parameter which affected weld soundness. Low filler metal feed rates with low levels of arc turbulence gave completely sound welds. High feed rates with a large amount of turbulence resulted in large voids [9].

In underwater welding there are many hydrogen and oxygen ions present and the possibility of substantial numbers of sodium, chlorine, magnesium, sulfur, potassium and calcium ions from the dissociation of sea water. In addition, if nitrogen gas shielding is used, care must be taken to avoid welding steels containing aluminum, chromium, vanadium, or molybdenum since a brittle nitrided structure could result [54].

The presence of oxygen in a weld will reduce strength, hardness and notch toughness, especially if dissolved in quantities greater than 0.1 percent. Since oxygen from dissociated water is so prevalent in underwater welding, deoxidants in electrode coatings become of critical importance [10]. As Table B-2 indicates, a noticeable reduction in carbon, manganese and silicon is observed as welding is carried out at progressively greater depths. It is apparent that pressure increases the rate at which these deoxidants combine with the oxygen generated from the dissociation of water. This leads to their proportionate removal from the weld metal[36]. It has also been reported that the chemical activity of silicon and manganese deoxidants increases with an increase in pressure. In welds made in aluminum under pressure, Rabkin et al. found that the concentration of the easily vaporized alloying elements, maganesium and zinc, increased as pressure was increased. This was due to the elevation of their boiling points and to a corresponding decrease in their rates of vaporization from the weld pool. An increase in zinc and magnesium concentration resulted in the elimination of defects caused by oxide inclusions and in a reduction in porosity [51].

B.1.6 Hydrogen Embrittlement

The severe quenching effect of the underwater environment and the presence of hydrogen in the weld area cause the most severe problems encountered in wet underwater arc welding. Although the quenching problem can be solved for certain applications by removing the water through the use of dry chambers and shrouds, the remaining moist atmosphere is still high in hydrogen. Shielding gases are used to overcome this difficulty in chamber welding, but it remains a problem in shrouded SMA welding as well as in all wet techniques. The combined effects of hydrogen and the quenching action result in a severe cracking problem in the heat affected zone (HAZ) and in a loss of ductility and tensile strength [11,36,45].

The quenching of the weld due to the large heat sink of the water is not a depth-related problem, but there are indirect depth effects. In the deep ocean the water is likely to be much colder than at the surface and the quenching effect is more severe [54]. Hydrogen embrittlement, which is depth-related, results in serious cracking only in hardened regions, such as those martensitic areas caused by quenching [16].

An underwater arc operates in a bubble atmosphere resulting largely from dissociation of the water by the extreme heat of the arc. This gaseous atmosphere may be up to 93 percent hydrogen [11]. The hydrogen dissociated from water in the bubble dissolves into the weld puddle and the rapid quenching action which enhances the formation of brittle martensite by a precipitation process also acts to prevent the hydrogen's escape. As the temperature cools down, the solubility of hydrogen is reduced and the hydrogen begins to diffuse out of the weld metal into the surrounding water and into the HAZ. The presence of both hydrogen and a hard martensitic structure in the same region, the HAZ, is an important point since hydrogen will not induce cracking unless the region is hardened and contains residual stress concentrations. Faster cooling rates and resultant higher hardnesses give the HAZ a higher susceptibility to hydrogen cracking [52].

TABLE B -2 Changes in weld composition with depth [36]

Depth (m)	Carbon (wt %)	Manganese (wt %)	Silicon (wt %)
20	0.26	0.63	0.16
40	0.19	0.21	0.08
60	0.09	0.12	0.03

Hydrogen embrittlement is most apparent at temperatures just above those of the ductile to brittle transition of the hydrogen-free metal. Below the transition temperature, the metal is brittle regardless of the presence of hydrogen and above this temperature it is difficult for micro cracks to form and propagate before plastic deformation can occur [16].

Although many theories have been developed to explain the mechanism of hydrogen embrittlement, the one advanced by Morlett, Johnson and Troiano seems to be generally accepted today [16]. This theory is based on diffused hydrogen localized at lattice imperfections known as voids. The severity of the embrittlement effect depends both upon the established stress system and the diffused hydrogen. The voids are regarded as micro notches about which a multiaxial stress system will be established when stress is applied to the steel. According to this theory, the stress system will be triazial in nature in a region within the metal lattice near each void. It is suggested that it is the hydrogen concentration within the void alone that determines the degree of embrittlement [16].

During diffusion, hydrogen concentrates in those regions of the lattice that are highly stressed. This creates a hydrogen concentration gradient which corresponds to the multiazial stress gradient of the region. However, once within the stressed region, equilibrium requirements cause the hydrogen to move from the lattice into the voids. The size of the hydrogen concentration gradient depends upon the original hydrogen concentration, the hydrogen diffusion rate and the time available for the diffusion of the hydrogen. One necessary condition for the diffusion of hydrogen through a metal is the dissociation of the hydrogen molecule to atomic hydrogen at the surface [52].

The diffusivity of hydrogen in metal can be expressed as an equation of the form:

$$D = D_o \sqrt{P \quad \exp(-Q/2RT)}$$

D = Diffusivity of hydrogen

D_o = Constant

P = Pressure of hydrogen

Q = Heat of solution

R = Gas constant

T = Absolute temperature

This equation, known as Sievert's Law, also governs the solubility of hydrogen in the weld metal [54].

It can be seen that diffusivity increases with temperature in accordance with the exponential law governing rate processes, and that diffusivity is also proportional to the square root of the hydrogen pressure. The hydrogen partial pressure in the arc bubble must be nearly as great as hydrostatic pressure since the bubble is more than 90 percent hydrogen and must have a total pressure equal to hydrostatic pressure. Thus, as

Figure B-8 illustrates, for a given temperature, the percentage of hydrogen in the HAZ increases as the pressure at which the weld is made is increased.

It has been suggested that the total amount of hydrogen which originally goes into solution in the weld metal must correspond to the maximum solubility of the metal. Since liquid metal has a greater gas solubility than solid, this results in greater initial absorption than would be expected using Sievert's Law. As a result, the diffusivity to the HAZ will increase over the values predicted by Sievert's Law. The rate controlling process for gas absorption proposed to replace Sievert's Law is the rate of gas ion supply to the metal surface [54]. Additional study to determine which of these two diffusivity relations is most useful in predicting the extent of hydrogen embrittlement should be undertaken.

Once embrittlement has occurred, a brittle micro crack may initiate in the region of high triazial stress. The exact manner by which the hydrogen concentration causes crack initiation is unknown. In fact, it is not certain whether the initiation occurs prior to, or after, the introduction of hydrogen [11]. Once the micro crack has been initiated, its propagation depends upon the hydrogen concentration, the triazial stress field and the plastic flow at the crack tip. The initiation enlarges to the size of a small crack which induces further stress on the crack tip, causing it to propagate. This crack may then grow in steps to critical size which can lead to brittle fracture and the resultant failure of the structure [52].

In most cases, of course, hydrogen-induced cracking does not lead to catastrophic failure. However, offshore structures made of higher strength steel have often suffered less dramatic cracking problems when repairs were attempted using single-pass wet welding techniques. It was not uncommon to be able to actually lift fillet welds made using wet processes out of the joint due to the severity of underbead cracking [45].

Porosity, due to hydrogen coming out of solution and forming small

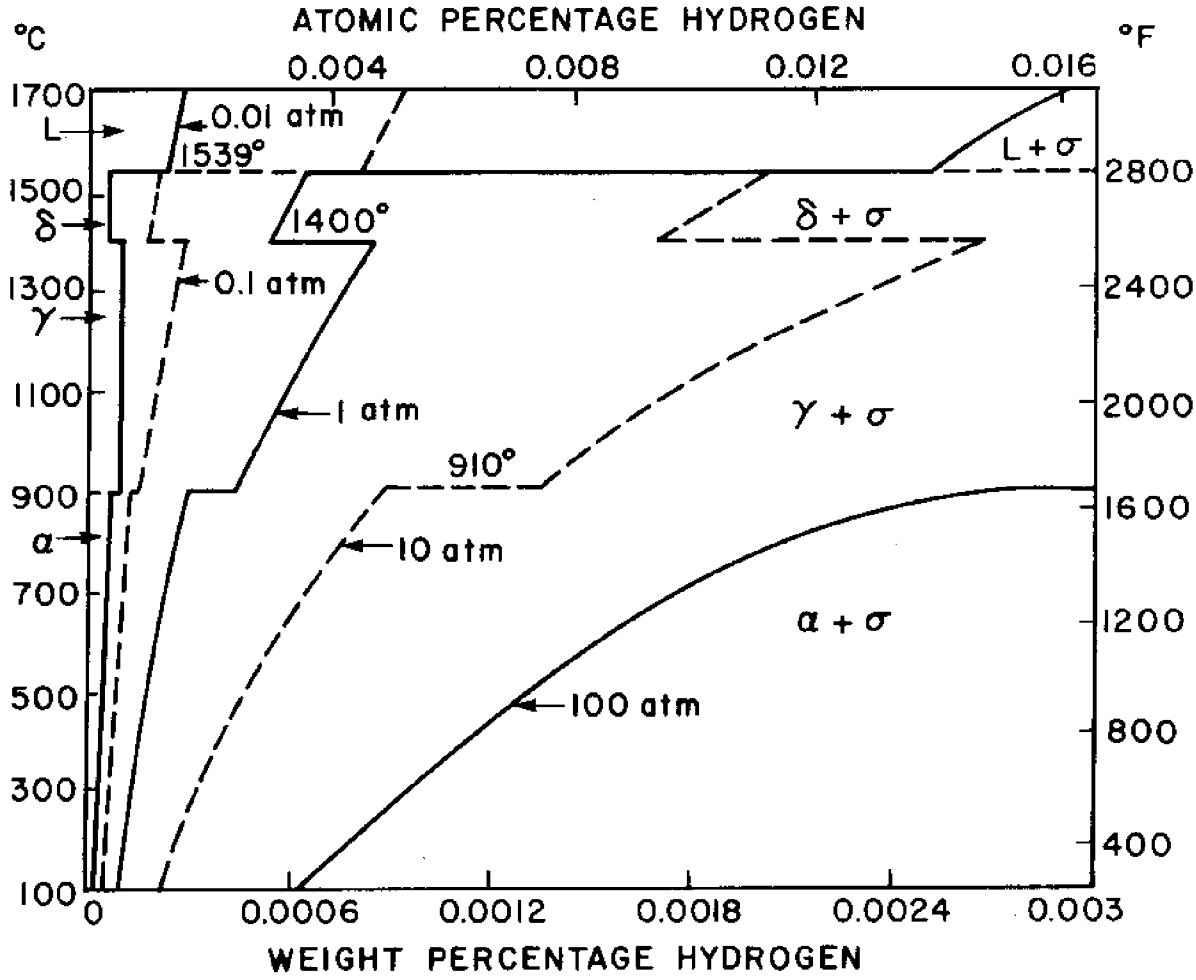


FIGURE B-8 Iron - Hydrogen equilibrium diagram voids in the weld area, can also occur. It is not a major problem in reducing the quality of welds made underwater. It has been found in experimental studies that increased pressure acts to retard the formation of pores in welds [8,51]. It is uncertain, however, whether this effect is due to the increased heat allowing the weld metal to remain molten longer, giving hydrogen additional time to escape, or to the increase in hydrogen solubility which results from increased pressure [8].

Two approaches have been tried to lessen the effects of hydrogen embrittlement. In steels having a high carbon equivalent (greater than 0.4 but less than 0.6) the use of austenitic electrodes has resulted in the elimination of underbead cracking during multi-pass underwater welding. This technique has proven reliable down to a depth of 80 feet and research to extend this depth to the 300 feet mark is underway [25]. An austenitic weld metal microstructure is capable of storing large quantities of hydrogen which, it appears, keeps the hydrogen away from the crack sensitive HAZ, avoiding underbead cracking [27]. A certain degree of success has been noted using post heat treatments for underwater welds. Some welds showed significant improvement after two or three hours at 250°C but others required much higher temperatures [36]. In another case, aging at ambient temperature for two days produced an improvement in ductility which was attributed to the escape of hydrogen from the weld area [27]. Another form of post heat treatment, tempering previous passes with later passes using multipass techniques has resulted in CBI being able to consistently produce high quality welds underwater [27]. It has also been suggested that preheating or insulating the work surface may help to reduce hydrogen related problems. Other possibilities include increasing the heat input to the weld arc without increasing weld size through the use of a wet GMA technique[10].

B.2 Exothermic Welding and Brazing

Exothermic processes exhibit several advantages which make them ideal candidates for application in the deep sea. Exothermic devices can be made which are small, inexpensive and contain their own power source. They can be placed either by submersibles, remotely controlled vehicles, or by divers and can be activated remotely. Several studies have been conducted on the feasibility of employing these devices for the placement of padeyes on objects prior to salvage [5,42,44]. In addition, it is possible that several other practical applications may arise since the mold in which the reacted thermit is cast is not strictly size or shape limited. One such possible application is the attachment of repair sleeves to damaged subsea pipelines.

An exothermic reaction is one in which metal oxides having low heats of formation are reacted with reducing agents which, when oxidized, have high heats of formation. Although there are many possible thermit reactions, the following is by far the most common:

$$3Fe_3O_4 + 8Al \qquad 9Fe = 4Al_2O_3 + 719.3 \text{ Kcal}$$

This reaction theoretically achieves a temperature of 5590°F but radiant heat losses and losses to the reaction vessel reduce this temperature to about 4600°F. Additions and impurities further reduce the temperature of the filler metal to around 3800°F. A temperature of about 2200°F is needed to initiate the reaction and is usually provided by an ignition powder which is ignited by a spark or an electric device [44].

The basic thermit reaction may be employed in one of several ways for joining. In fusion welding, the most common method, the thermit is reacted in a chamber and tapped into a mold only after the reaction is complete and slag separation has occurred. A portion of the molten metal flows completely through the mold and into an overflow chamber in order to provide for surface cleaning and preheating. The remainder is held between the surfaces to be joined by the mold and forms the actual weld. By employing appropriate molds, welds of various sizes and configurations can be accomplished [5].

Pressure thermit welding utilizes the molten metal and slag to provide the necessary heat to join the surfaces, but not to add material to the weld. The heat content of the thermit products is used to bring temperatures up to the forging level, at which time pressure is applied to form a bond [5].

Thermit brazing also uses the thermit mixture strictly for its heat content. After the parts to be joined are heated, a flux is used to clean the surface and a brazing material flows between the parts by capillary action [45].

Just as in the more common arc technique, cooling rates have a significant influence on the resulting hardness of a thermit fusion weld. Rockwell "B" hardness climbed considerably as the cooling rate was increased [5].

The underwater environment has other effects on thermit processes. Water must be removed from the weld area prior to tapping any molten metal into the area if a sound weld is to be achieved. This may be accomplished by removing the water through displacement by a pressurized gas or by preheating the area through the use of a separate thermit reaction timed to ignite just prior to the primary reaction. It has been found that the flow of molten metal through the mold can effectively remove minor oxidation and dirt from the surfaces to be joined. Surface preparation may then be kept to a minimum [44].

One major depth-related problem, offsetting the pressure differential between reacting chamber and mold in order to provide for the flow of molten metal, must be solved before thermit processes can be considered practical alternatives for deep ocean application. Surface thermit welding devices rely on gravity induced flow of the molten metal from the reaction chamber into the mold. In a confusing and crowded underwater environment, such as that found in many salvage situations, proper orientation of the device for gravity flow cannot always be assured. In addition, the mold is subjected to ambient pressures while the reacting chamber must be kept dry. The thermit reaction itself cannot be used to help offset this pressure differential since none of the products of reaction are gaseous. As a solution to this problem, pressurizing the thermit reaction chamber to a level slightly higher than ambient pressure, prior to leaving the surface, has been suggested [5]. It is hoped that the slightly greater pressure in the reaction chamber will then be sufficient to overcome the ambient pressure and to induce flow of the molten metal into the mold. In order for this method to work properly, however, the level of pressurization will have to be calculated rather precisely. If chamber pressure is too low, no flow will occur; if too high, the mold may be damaged or forced off the surface. Measuring the exact depth at which an attachment point is required also adds complexity and expense to a salvage situation.

B.3 Explosive Welding

Developmental work is now being conducted to develop an explosive welding technique suitable for the deep ocean. It is believed that this process may be useful in attaching padeyes to sunken objects to aid in salvage efforts. If development is successful, this device has several advantages which may be exploited for deep application. First little manipulative ability is demanded; in fact, only emplacement and remote denotation are required. Next, the power source for this device is small and self-contained. Finally, the process is simple and inexpensive.

The principle of explosive welding is simple. It has been found that two pieces of metal impacted together at sufficient velocity can form a weld at the interface. An explosive charge provides enough velocity to ensure bonding. Figure B-9 depicts the basic arrangement required. The upper or flyer plate is projected against the stationary lower plate or target by the force of an explosion, forming a weld in microseconds with a noticeable lack of overall deformation. There must be a slight angle between flyer plate and target, usually less than five degress, and the flyer plate may be supported a small distance away from the target. The flyer plate is protected by a rubber or P.V.C. plate, known as an attenuator, which is placed between it and the explosive. A stand-off distance is required for a single explosive charge. Sheet or plastic explosives used for larger area bonding are placed in contact with the attenuator and ignited from the end where clearance between flyer and target is the least. Surface preparation is not critical but deeply pitted, scaly, corroded or roughened surfaces should be avoided [31].

There is considerable plastic deformation in the immediate region of the faying surface and the hardness of the deformed interface is usually greater than that of the unwelded material. This interface assumes a wavy form with wave amplitudes of from 0.005 to 3/16 inch and wavelengths of from 0.01 to 1/4 inch, depending on welding conditions. Satisfactory welds seem to require the formation of waves. A small jet of metal, known as a surface jet, is often ejected from between the plates as they fold together. The ripples and jet are caused by the high pressures and instantaneous temperatures of the explosive impact, which results in the metal near the bonding front becoming sufficiently plastic to act as a fluid. Under these conditions, the flyer plate acts as a jet traveling

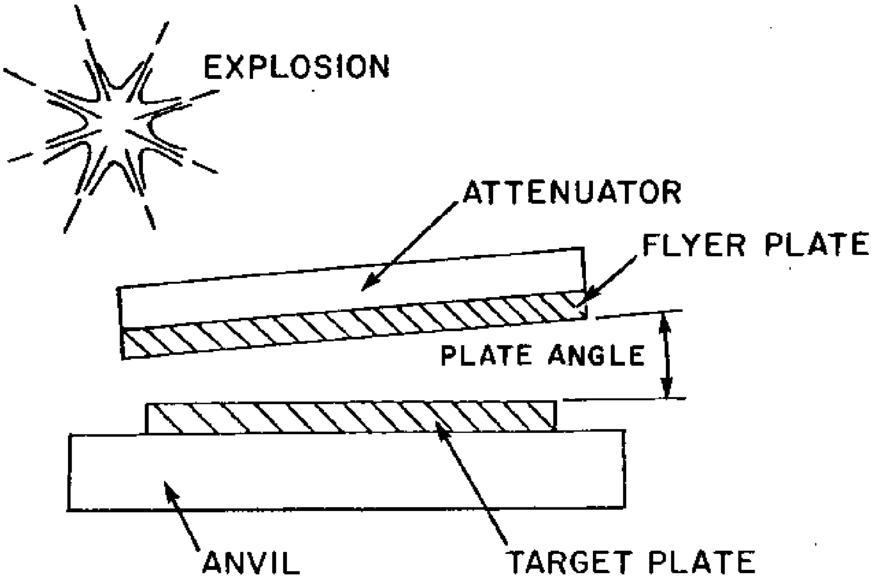


FIGURE B-9 Arrangement for explosive welding across the target plate. Humps are raised in the target region ahead of the jet, then are passed over while new humps form. This causes the rippled or wavy weld interface. Division of the jet as it strikes the surface results in surface jetting and also in stripping the surface of the contacting plates, exposing metal for bonding [31].

In the particular technique employed underwater, a second charge, which is timed to detonate a small fraction of a second prior to the main charge, is placed in such a manner as to evacuate the water between the plates. However, as welding depths are increased, progressively larger secondary charges will be needed to evacuate the water since larger pressure forces will be acting to resist evacuation. This presents a real problem since the nearly incompressible water will transmit larger and larger shock waves to the plates as the size of the secondary charge is increased.

In making attachments to highly corroded objects some form of surface preparation must be considered. It is possible that still another charge, properly applied, might achieve this.

One final disadvantage common to both surface and underwater explosive welds should be noted. Welds with good bonding characteristics are difficult to produce consistently. This process appears to be highly sensitive to variations in welding conditions such as the plate separation distance and angle, the explosive standoff distance and the balance between the magnitude of the explosive force and the surrounding environment. Difficult to control precisely in laboratory conditions, these factors may become prohibitive in actual deep sea work [43].

B.4 Velocity Power Tools

Several velocity power tools have been fully developed for use underwater in salvage and emergency repair work. These devices may be used to attach studs or lifting points, to provide fittings for gas or liquid transfer and to punch holes. Velocity power tools are small, inexpensive, flexible and have a self-contained energy source. Several models have been developed. Of these, two have been designed strictly as diver tools while a third has been designed for remote operation in conjunction with the navy's LOSS program. These tools can be used on wood, concrete and sheet metal in addition to steel plate.

Each velocity power tool is essentially a gun. As Figure B-10 illustrates, a stud or other device acts as the projectile. It is attached to a piston which is propelled by the detonation of gunpowder within a standard cartridge. The tool itself uses a trigger and firing pin assembly to detonate the cartridge and propel the piston and projectile down the barrel. Several safety devices are incorporated into each diver operated tool to ensure that premature firing cannot occur. The diver must, before firing, align the barrel assembly in a certain manner and push the barrel against the work with a force of at least five pounds and at an angle of between 82 and 90 degrees [37].

There are several types of ammunition available for each tool. These include several types of solid studs used for fastening, hollow studs used to transfer a gas or liquid through a bulkhead and a hole punch projectile used to punch a hole through a plate. Each type has a number of powder loads to accommodate plates of various thicknesses [37].

The light-duty diver tool operates with a flooded barrel and can be used at depths up to 300 feet. It can be reloaded simply underwater by placing a new projectile-cartridge assembly in the breech. The heavy duty diver tool and the remotely operated tool both operate with sealed barrels in order to accelerate the projectile sufficiently to achieve the required penetration. The heavy duty diver tool can only be reloaded underwater by replacing the entire sealed barrel unit [37]. The present depth capability of sealed barrel units is 1000 feet but it should be possible to extend this limit if the need arises.

Velocity power tools are ideal for attaching temporary patches. One of two methods may be employed. Using the first method, a patch can be essentially nailed to a structure by firing a stud entirely through the patch into the structure. The second method consists of firing studs through predrilled holes in the patch and into the underlying structure. The patch can then be bolted on. Centering plugs on the muzzle of the barrel ensure stud alignment with the hole. Patches and other fittings applied using these tools are capable of withstanding large forces. Average extraction forces for heavy and light weight studs and various plate thicknesses are tabulated in Table B-3. Loading these studs in shear, rather than tension, increases their load-bearing capacity since pull-out cannot occur. This is done in the Navy's LOSS system.

The primary disadvantage of the velocity power tool is its basically destructive nature. The projectile literally rips its way into the parent structure. Careful matching of powder loads for intended use minimizes the damage, but a stud or other fitting attached in this manner cannot be considered a permanent part of the structure. Crevices and discontinuities are created which serve as sites for corrosion. This technique is thus limited to salvage and temporary repair. Even in certain salvage situations,

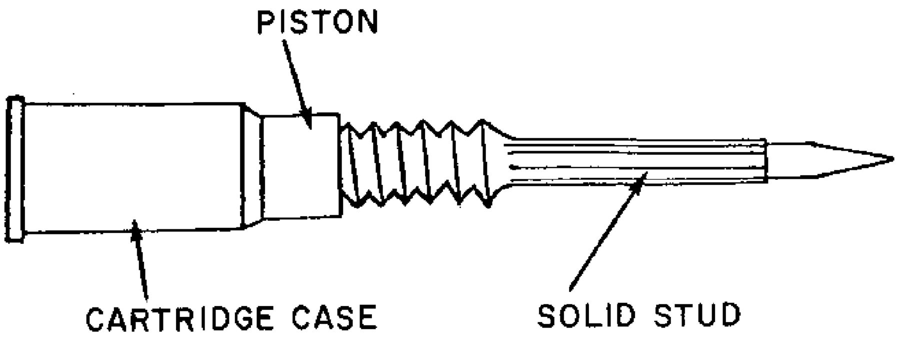


FIGURE B-10 Solid stud cartridge

the destructive nature of this tool is a disadvantage. If this device were used to provide an attachment point on a watertight compartment of a sunken submarine or submersible, it could cause leakage or even collapse of that compartment. This danger increases as salvage depth is increased.

B.5 Other Processes

There are several processes, other than those outlined above, which are being considered or may in the future be considered for deep ocean use. However, little technical information dealing with the effects of pressure on these techniques is available so only a rather cursory summary will be presented.

TABLE B-3 [37] Velocity power tool stud extraction forces for structural steel plate

Heavy Duty Solid Studs	
Plate Thickness	Average Extraction Force
3/8 in.	8,000 lbs.
1/2	14,000
5/8	16,000
3/4	19,000
7/8	22,000
1	26,000
1 1/8	29,000
Light Duty Solid Studs	
1/4 in.	3,000 lbs.
3/8	3,500
1/2	4,000

B.5.1 Mechanical Joining

Mechanical joining techniques form the heart of several repair systems being developed for the deep sea. These systems, which will be used in the repair of submerged production equipment and pipelines, were discussed in Chapter 2. Mechanical joining methods possess several advantages over other techniques for deep ocean application. First, they are well within the state of the art, requiring little or no developmental effort. Some of these methods are also simple enough to be easily employed by remotely operated manipulator systems. Finally, these methods are reliable and their results consistent. They can be especially designed for the repair of particular subsea structures.

Mechanical connectors may find their greatest undersea use in the repair of pipelines. Many pipe repair devices have been developed over the years to meet surface requirements for repair techniques in locations where welds could not be made. These devices include mechanical sleeves for bolting and sealing two pipe ends together, split sleeves for the repair of ruptured pipelines, clamps for fixing small leaks and mechanically connected hot tapping saddles. Many present devices rely on multiple bolts and are therefore more compatible with divers than with remotely operated maniuplators. However, new connectors which snap together, yet are capable of containing high pressure flow, are being developed [29].

Mechanical joining devices are also suitable for use in conjunction with other techniques. For example, a sleeve may be mechanically connected and sealed around a pipeline so that flow may be restored. A reinforcing seal weld can then be made between sleeve and pipeline without the danger of explosion which is present when gases cannot be vented from an enclosed space.

B.5.2 Gas Welding

Attempts which have been made to use gas welding processes underwater have met with little success, even though such gases as oxygen-acetylene, propane, methane, ethane, and ethylene have all been tried. Acetylene, in fact, becomes unstable at depths greater than 5 to 10 meters due to increased pressure and can be considered safe only at pressures less than 10 decibars [54].

Hydrogen is the only gas which may be useful for deep ocean use since all other fuel gases liquify under ambient pressures at shallow depths. A hydrogen-oxygen combination may prove useful for some applications down to around 1500 meters. Below this depth, even heating units are no longer a feasible means of keeping the hydrogen in a gaseous state and liquification occurs [54].

B.5.3 Adhesive Bonding

Adhesive bonded joints have been used for many structural applications especially in the aerospace industry [50]. This technique is amenable to remote operation and requires no external power source. In addition, it may be accomplished with little or no external heat curing [45].

Adhesive bonding occurs primarily as a result of the molecular attraction exerted between the surface to be bonded and the adhesive. Primary chemical and electrostatic forces of attraction form most adhesive bonds, thus suggesting that the strongest bonds are obtainable between highly polar materials. Metal surfaces, although not highly polar by themselves, mirror the forces in a highly polar adhesive placed on them, resulting in a strong bond [50].

There are a number of adhesives that offer promise for underwater joining. These include butyl rubber-quinoid cure, nitrile rubber-epoxy, polysulfide-epoxy and epoxy-polyamide. Most of these cure at or near 70°F so, in practice, they must either be placed in a heated enclosure or limited to warm water applications. Additional problems which must be overcome include:

1. Rigorous surface preparation of joints

2. Joint fitup
3. Joint design
4. Methods of introducing adhesive to the joint
5. Curing techniques
6. Strength of joints produced

APPENDIX B
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APPENDIX C

MECHANISMS OF RAPID COOLING AND THEIR DESIGN CONSIDERATIONS IN UNDERWATER WELDING

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APPENDIX C

Mechanisms of Rapid Cooling and Their Design Considerations in Underwater Welding

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K. Masubuchi, Massachusetts Inst. of Technology

Introduction

During the last several years, systematic research efforts on underwater welding have been made at the Dept. of Ocean Engineering of the Massachusetts Inst. of Technology. Most of the research programs were funded by the National Sea Grant Office of the National Oceanic and Atmospheric Admin. Some of the reports, theses, and papers have been published.[1,2] The research programs have covered various subjects including basic research on mechanisms of underwater welding as well as development of new, improved processes. This paper discusses one subject: rapid cooling during underwater wet arc welding.* This paper has been prepared primarily from results obtained in research by Tsai.[4]

The major portion of Tsai's research is composed of extensive mathematical analyses of heat flow during underwater wet arc welding. A series of mathematical equations has been developed to analyze all pertinent phenomena involved: dynamics of bubble formation, heat-loss mechanisms, etc. Experiments were made to examine the validity of the analyses. Studies were made to investigate effects of various parameters (welding conditions, plate thickness, etc.) on cooling rates in weldments, especially in the heat-affected zone (HAZ). Studies also were made to evaluate the effectiveness of various methods of reducing the cooling rate.

Since details of analytical and experimental results are included in Ref. 4, this paper presents a brief summary of the analysis and some experimental results. The emphasis of this paper is placed on information of practical importance.

Brief Summary of Cooling Mechanisms in Underwater Welding

The mode of heat transfer in underwater welding is quite different from that in air welding. The existence of dynamic bubbles during underwater welding induces a flow field around the welding arc. This water flow along with the agitation of bubbles carries the heat away quickly from the base material and causes the rapid cooling phenomenon. In this section, buble dynamics and heat-loss mechanisms are discussed.

Underwater Bubble Dynamics

Bubble generation due to the high concentration of heat in the arc and its departure and final collapse during the underwater arc welding process in the wet condition was investigated by a high-speed cinematography study at the Massachusetts Inst. of Technology.[1] The arc energy is intense, and water

Rapid cooling is an inherent problem in underwater welding. This paper discusses the basic understanding of cooling mechanisms during underwater welding and the effectiveness of various methods of reducing the cooling rate. Numerical results obtained from a computer analysis are used to discuss the design criteria and the effect of various parameters on the cooling rate.

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*Hydrogen-induced cracking is another important problem associated with underwater wet welding and is discussed in a separate paper.[3]

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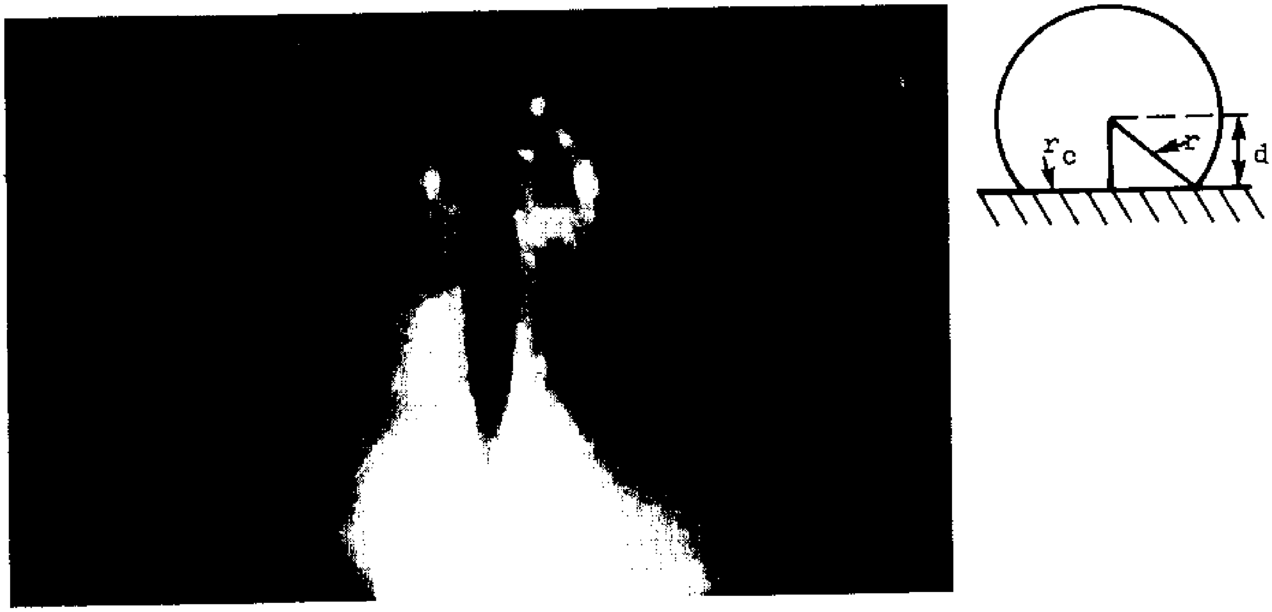

Fig. 1 – Underwater arc-bubble growth.

surrounding the arc is vaporized immediately and forms a relatively stable bubble void. Gases decomposed from the flux coating or vaporized from the surrounding water cause the bubble to grow. The bubble grows and rises continuously until its radius becomes tangent to the initial void, at which time the bubble breaks away and a new bubble begins to form. The welding arc always is protected by the bubble during welding. The shape of the bubble, especially late in its growth, may be assumed to be spherical.

To predict bubble phenomena mathematically, an idealized bubble-growth model with bubble formation from an orifice can be simulated.[1] It assumes that the bubble growth begins at a point on or just above the plate and that the gas behaves ideally. Only the balance of buoyant and inertial forces need to be considered. Large flow rates make it possible to neglect surface tension. Fig. 1 shows the actual bubble growth and defines the terms of bubble geometry.

The characteristics of a dynamic bubble can be defined by the following three equations.

Rising velocity of a bubble:

$$\frac{de}{dt}=\frac{8}{11}gt. \quad \text{(1)}$$

Bubble growth rate:

$$\frac{dr}{dt}=\frac{q}{4\pi t^{2/3}}. \quad \text{(2)}$$

Height of a departing bubble:

$$h_{\max}=r_{\max}+r_o. \quad \text{(3)}$$

$r_{\max}$ is the radius of a departing bubble, and r_o is the radius of a stable gas void.

The volume flow rate of vapor, q, is directly proportional to the heat input rate from the arc and its environmental conditions (water temperature and water pressure). In mathematical expression,

$$\begin{aligned} q &= q_{\text{vapor}}+q_{\text{gas}} \\ &= \frac{\dot{Q}_v R_v T}{L_v P}+\dot{m}_f\frac{R_g T}{P}, \quad \text{(4)} \end{aligned}$$

where $\dot{Q}_v$ is the heat input rate used to vaporize water, R_v and R_g are gas constants of water vapor and decomposed gas, respectively, and $\dot{m}_f$ is the mass of supplied shielding gases.

Direct measurement of q is very difficult. q_{gas} is the only substance which can be measured by experimental collection of gases filtered through the liquid above the water surface. Water vapor eventually is condensed before the bubble rises to the water surface, but it is very active during the rapid bubble-growth process and augments the apparent flow rate.

The volume rate can be written explicity in terms of bubble frequency:

$$q=\frac{4\pi}{3}r_{\max}^3\cdot f_{\text{bubble}}. \quad \text{(5)}$$

The maximum bubble radius, $r_{\max}$, and the radius of stable void, r_o, can be measured by a high-speed photographic technique. The maximum height of a bubble can be determined using Eq. 3, and the period of a dynamic bubble (bubble frequency) can be obtained from Eq. 1. Volume flow rate, therefore, is determined by Eq. 5. Table 1 shows good agreement of bubble growth between measured data using high-speed photographic technique and the theoretical predictions using Eqs. 1 through 5.

Heat-Loss Mechanisms

Keeping track of all the energy emitted by the

TABLE 1 – BUBBLE GROWTH CHARACTERISTICS
(E7014 electrode)

	Measured*	Calculated
r_o	0.5 cm	0.5 cm (measured)
Period	0.076 seconds	0.071 seconds
Frequency	13 bubbles/s	14 bubbles/s
q	60 cm^3/s**(= 134 cm^3/s by calculation)	134 cm^3/s
r_{max}	1.31 cm	1.31 cm
e_{max}	1.83 cm	1.81 cm

*Measurement was done by a high-speed motion picture study conducted by A.J. Brown at the Massachusetts Inst. of Technology in 1973.

**Measurement was done by collection of gases which have filtered through the liquid. Water vapor generated at the arc eventually was condensed, leaving only hydrogen and organic by-products filtered through the liquid.

welding arc is a difficult task. The energy acts to preheat, melt, and postheat the weld metal and eventually is dissipated in a number of ways.

The energy balance in the molten pool area is discussed in Ref. 4. In air welding, the heat losses from the molten surface outside the heat input circle are basically due to radiation. Heat losses from the surface some distance from the arc are due to natural convection. This was proved experimentally.[4]

In underwater welding, very fast cooling in the weldment usually is experienced. According to the observation of the high-speed cinematography, heat losses during underwater welding are mainly due to heat conduction, which transports heat from the plate surface into the moving water environment, the motion of which is created by the rising gas-bubble column in the arc area. No boiling phenomena were observed anywhere except in the arc-bubble zone. Accordingly, the heat-loss mechanism is basically dependent on the water flow field, which is a function of gas formed in the arc and its flow rate.

The boundary heat losses in underwater welding can be correlated using a semiempirical technique. When considering two-dimensional solutions for welding heat flow in thin plate, the general equation to be solved is

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{V}{\alpha}\frac{\partial T}{\partial \xi} - \frac{h(\xi,y,T)}{\bar{k}_h d}(T - T_o) = 0, \qquad \text{(6)}$$

where $\bar{k}_h$ and α are temperature-dependent thermal properties. h is the heat-loss coefficient, which is temperature and/or location dependent. Expanding Eq. 6 into difference approximation and regrouping the terms, h can be written as

$$h(\xi,y,T) = \left[\frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{(\Delta\xi)^2} + \frac{T_{i,j+1} - 2T_{i,j} + T_{i,j-1}}{(\Delta y)^2} + \left(\frac{V}{2\alpha_{i,j}}\right)\frac{T_{i+1,j} - T_{i,-1,j}}{\Delta\xi}\right] \cdot \frac{K_{i,j} d}{(T_{i,j} - T_o)}, \qquad \text{(7)}$$

where $T_{i,j}, T_{i+1,j}, T_{i-1,j}$, etc., are measured temperatures at points (i,j), $(i+1,j)$, $(i-1,j)$, respectively. Thermal properties are taken at the temperature $T_{i,j}$.

After careful examinations of existing data from various sources, it has been decided that the following formula be used to express the average heat-loss coefficient, $\bar{h}_T$.

$$\bar{h}_T = 675(T_w - T_o)^{1/4} \qquad \text{(8)}$$

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After careful examinations of existing data from various sources, it has been decided that the following formula be used to express the average heat-loss coefficient, $\bar{h}_T$.

$$\bar{h}_T = 675(T_w - T_o)^{1/4} \qquad \text{(8)}$$

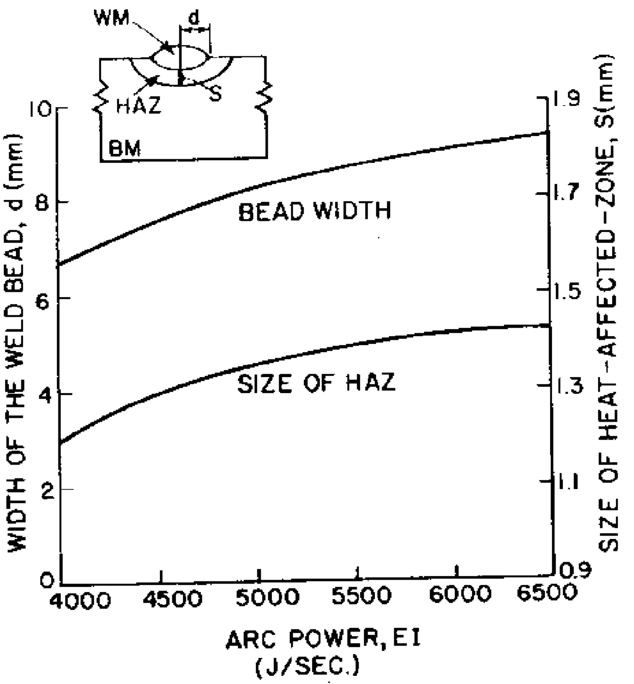
It has been found that the conductive heat losses due to water motion are much higher than that due to natural convection with boiling.

The heat-loss mechanism in the dynamic arc-bubble is not understood fully. Mathematical analysis for this region is very difficult. Therefore, it is assumed that there is no heat loss inside the heat-input circle. Outside this circle, Eq. 8 can be applied.

Parametric Study of Cooling Phenomena in Underwater Welding

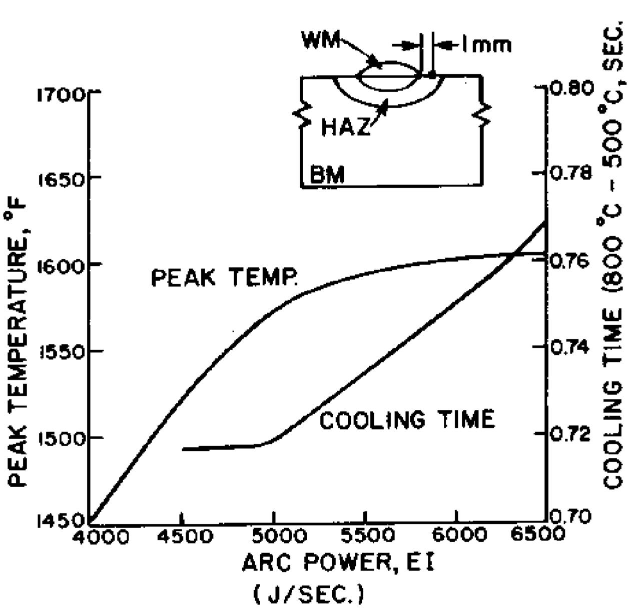
According to the study conducted by Tsai,[4] welding variables influencing the thermal responses of the material can be related indirectly to the cooling rate in the HAZ through three weld geometrical parameters: bead width, bead penetration, and bead ripple length. In this section, effects of four variables on cooling rate in the HAZ of a bead-on-plate weldment are studied using Tsai's numerical approach.[4] The four variables are welding arc power, welding speed, thickness of base plate, and water temperature.

The weld geometrical parameters are determined experimentally with respect to a specific variable change and used as the input information in the numerical analysis. According to limited available data generated in Ref. 4, experimental correlations of



1/8" - THICK PLATE 9 IPM WELDING SPEED
WATER TEMP. 82 °F

Fig. 2 – Effect of arc power on bead width and size of the HAZ.



1/8" - THICK PLATE
9 IPM WELDING SPEED
1mm FROM THE FUSION LINE
WATER TEMP. 82 °F

Fig. 3 – Effect of arc power on the peak temperature and cooling rate (800 to 500°C).

arc power, welding speed, and plate thickness are summarized in this section.

At low welding speed, the weld penetration and ripple length do not change with arc power. Since the material below the molten pool surface and the material in the pool of solidification are not exposed directly to the arc heat, the heat required to melt the material in these regions is transferred by conduction and convection in the pool. A change of arc power at low welding speed does not deepen penetration or increase melting at the trailing edge of the molten pool.

However, at high welding speed, a higher arc power would increase the penetration relatively because it is easier for heat to reach the material to be melted due to high convective heat-transfer rate (caused by fast arc motion) in the pool. The arc power change has little effect on the ripple length at high welding speed.

The bead width increases with an increase of the arc power. The point of maximum width in the molten pool usually is exposed under the welding arc. For example, the radius of heat-input circle is 0.7 cm and the distance to the point of maximum width from the origin (center of the electrode) is 0.64 cm in an underwater shielded metal-arc welding process[4] (E7014 electrode, 4.76-mm wire diameter, 200 A). Therefore, melting of the material inside the heat-input circle is a strong function of the arc power and its distribution.

Effect of Arc Power

Fig. 2 shows the effect of arc power on the size of the HAZ and the bead width. Size of the HAZ is the width of the zone measured on the direction of plate thickness. The bead width is increased by 2.5 mm and the size of the HAZ is increased by 0.25 mm when the arc power is increased from 4000 to 6500 J/s.

Fig. 3 shows the effect of arc power on the peak temperature and cooling rate from 800 to 500°C at a point 1 mm from the weld fusion line on the plate surface. The peak temperature increases with the increase of arc power. The cooling rate decreases by a small amount (0.05 seconds). A change of arc power alone would not reduce the cooling rate in the HAZ effectively.

Effect of Welding Speed

Fig. 4 shows the effect of welding speed (5000 J/s arc power) on size of the HAZ and the peak temperature at a point 1 mm from the fusion line on the plate surface. Welding speed higher than 4.23 mm/s seems to cause unreasonably low temperature and to result in a small bead.

The cooling rate from 800 to 500°C at the same point (1 mm from the fusion line on the plate surface) is 0.72 seconds when the welding speed is 3.81 mm/s. It becomes 1.23 seconds when the welding speed is 2.54 mm/s. A small decrease in welding speed in underwater welding could reduce the cooling rate in the HAZ to some extent.

Effect of Plate Thickness

Fig. 5 shows the cooling time and peak temperature at a point 2 mm from the fusion line in the weld center plane vs. plate thickness. For thin plates, increasing the arc power does not affect the cooling rate. However, it reduces the cooling rate when the plates become thicker. A similar result obtained experimentally by The Welding Inst. is shown in the same figure.[5] Good agreement is shown.

Effect of Water Temperature

The water temperature on the working site in the North Sea is 6 to 7°C on the average. It was reported that higher arc voltage and stronger arc force existed during welding in cooler water.[2]

If the molten pool remains invariable with the change of water temperature, numerical analysis shows minor change in cooling rate and peak temperature in the HAZ. Fig. 6 shows the effect of water temperature on peak temperature and cooling rate at a point 1 mm from the fusion line on the plate surface.

The direct effect of water temperature on the cooling rate in underwater welding is imposed on the boundary heat loss, but it is small. Any indirect connections through the change of the molten pool require further study.

Study of Cooling Rate in the HAZ

Fig. 7 shows the numerically predicted iso-cooling lines (800 to 500°C) in the HAZ of an underwater weld. High cooling rates appear in the areas near the plate surface. This phenomenon indicates the dominant effect of heat transfer due to dynamic bubbles. Heat exchange between the water/plate interface is more significant than heat transmission due to thermal conductivity in the base metal in determining the cooling rate in the HAZ.

Fig. 8 shows the peak temperatures and cooling rates along the thickness direction in the weld center plane for welding a 6.35-mm thick plate. Peak temperature decreases as the distance from the fusion line increases. Cooling rate decreases in a similar way.

Methods of Reducing Cooling Effect in Underwater Welding

Two methods can be used to control the cooling rate in underwater welding: (1) adjusting the welding conditions and (2) insulating or removing water from the joint material. An increase of arc power in the normal operating range in underwater welding does not reduce the cooling rate effectively. If the arc power used is beyond the normal operating range, unsatisfactory weld bead may result from excessive melting and too much spattering.

A more efficient way to reduce cooling rate in underwater welding is to use slower welding speed. A small decrease in welding speed can reduce the cooling in the HAZ to some extent. However, to slow the welding speed would increase the production time tremendously.

Insulating or removing water from the joint material is probably the only effective and practical way to reduce the rapid cooling effect in underwater

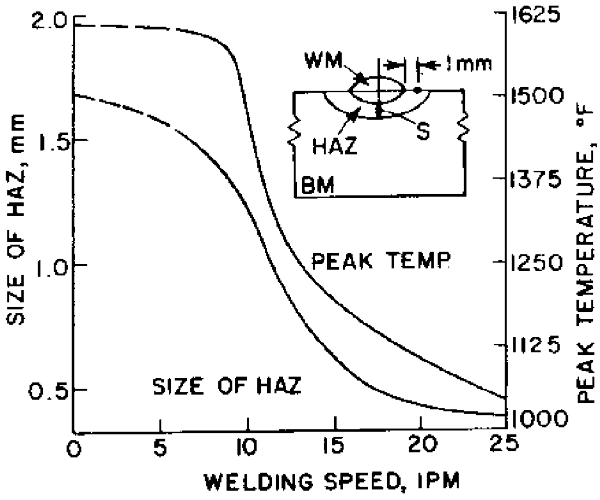


Fig. 4 – Effect of welding speed on size of the HAZ and peak temperature at the point 1 mm from the weld fusion line.

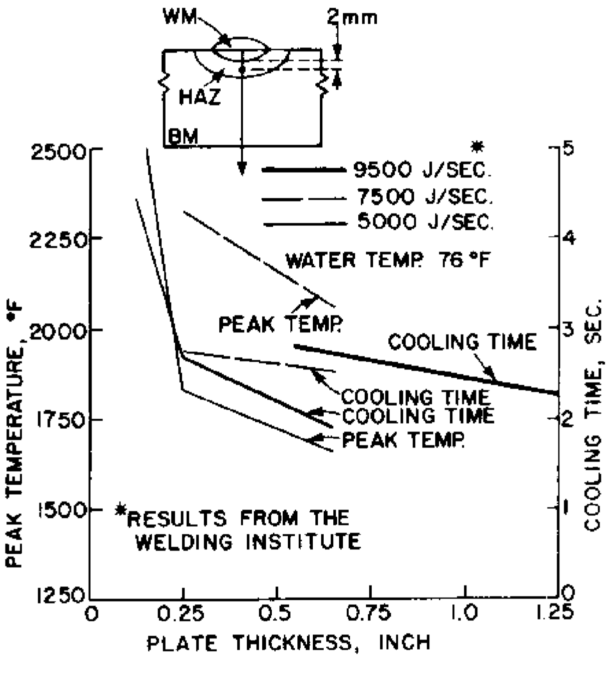


Fig. 5 – Effect of plate thickness on peak temperature and cooling rate (800 to 500°C) at a point 2 mm from the fusion line in the weld center plane.

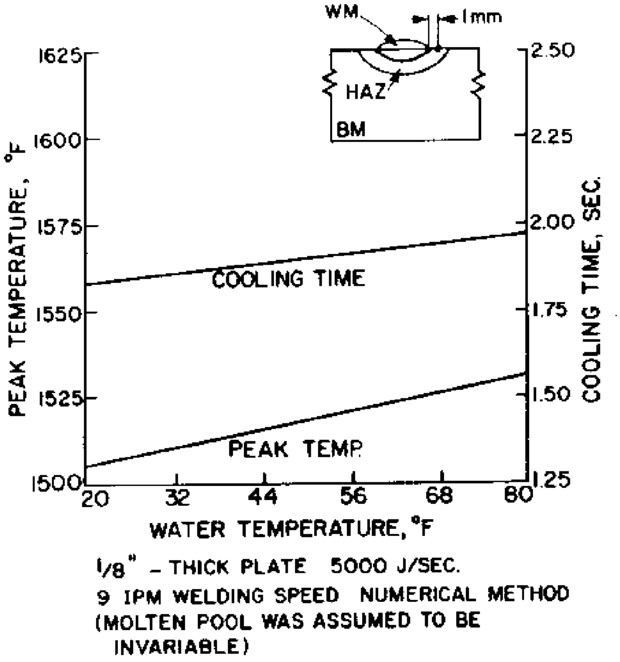


Fig. 6 – Effect of water temperature on the peak temperature and cooling rate (800 to 500°C) at a point 1 mm from the fusion line on the plate surface.

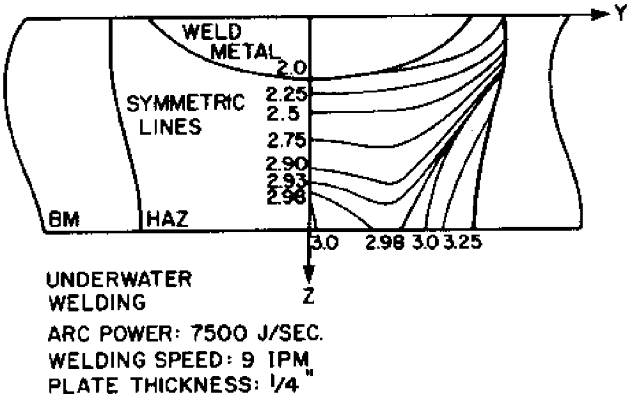


Fig. 7 – Calculated iso-cooling lines in underwater weld, cooling time in seconds from 800 to 500°C.

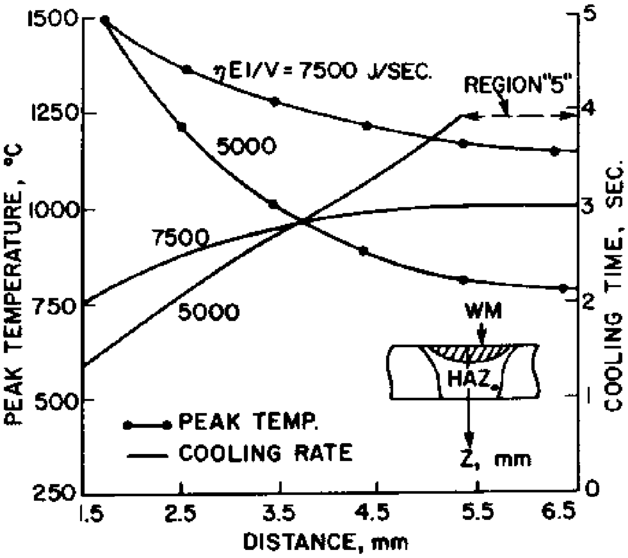


Fig. 8 – Peak temperature and cooling rate (800 to 500°C) along the thickness direction in weld center plane (1/4-in.-thick plate).

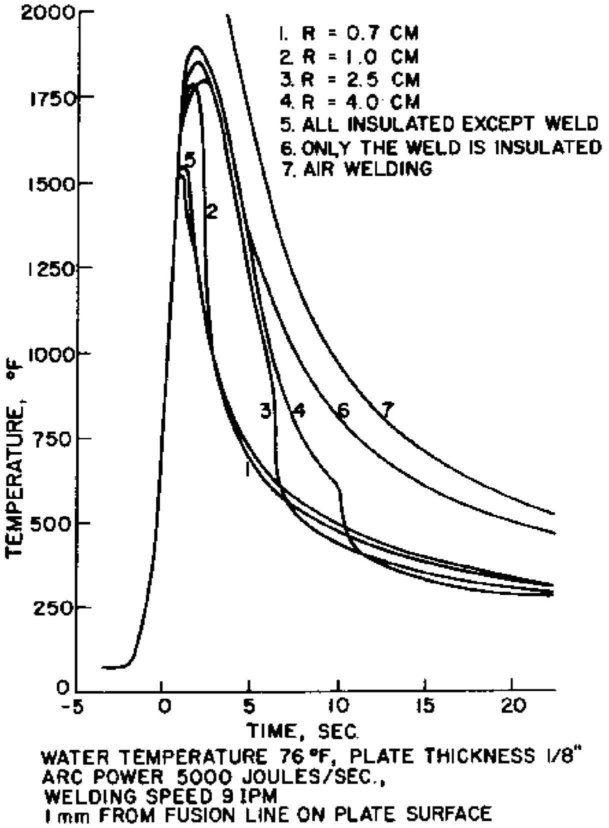


Fig. 9 – Effect of insulation on temperature profiles.

welding. The newly developed underwater welding processes, including water-jet and hydro-weld processes, are based on the same principle. However, it was found experimentally that most of the heat loss during underwater welding was from the face of the plate in downhand welding. Insulating the bottom of the plate produced marginally improved results over the face-insulated plate.[2]

Three methods of insulation were studied by computer analyses conducted by Tsai[4] (see Appendix): (1) full insulation over the plate except the weld bead, (2) local dry spot (water-jet simulation), and (3) insulation over the weld bead and its vicinity (flux-shielded and hydro-weld simulation).

Fig. 9 shows the cooling curves of different approaches. The first method (Curve 5) shows little improvement in changing the temperature profile. The local dry-spot method appears to have a minimum size of water-removing area. Fig. 10 shows that the critical radius of the water-removing area is 2 cm. Any attempt to remove water to create a dry spot smaller than the critical size will result in an even higher cooling rate. This phenomenon can be explained by Figs. 9 and 10. The peak temperature is increased drastically due to the small dry spot. This temperature is observed in a time delay of about 0.5 second. (The time for this point to reach the peak temperature shifts to the right on the time scale.) The point of 500°C is located 1.15 cm after the arc (3 seconds) in a normal wet welding. If the dry spot is too small to cover the point of 500°C effectively, the time required to reach this temperature shifts to the left on the time scale. Consequently, the cooling rate is increased.

The size of the water-jet nozzle is restricted by its partial sealing function. Within a 5-cm radius range, the cooling rate can be reduced only up to less than 1 second. Instead of reducing the cooling rate, weld hardness sometimes is found to be even higher due to the postcooling effect resulting from the impinging water.

Fig. 9 also shows that insulation over the weld bead (along the weld center line) can raise the cooling time in the HAZ up to more than 4 seconds (Curve 6). This result validates the speculation that insulation of the weld bead effectively can improve the cooling rate in underwater welding.

Shown in Fig. 11 are the cooling characteristics of all three insulation techniques on a continuous-cooling-transformation (CCT) diagram. Full martensitic structure would form in the HAZ in normal underwater wet welding.

Design Considerations and Conclusions

Arc in Underwater Environment

According to the experimental observation, the underwater welding arc can be maintained only when the arc is surrounded completely by a dry gaseous environment. This dry environment may be formed by the decomposed or supplied shielding gas and the water vapor. Heat losses to the water environment directly from the column are not as great as thought. The arc efficiency is about 0.8.

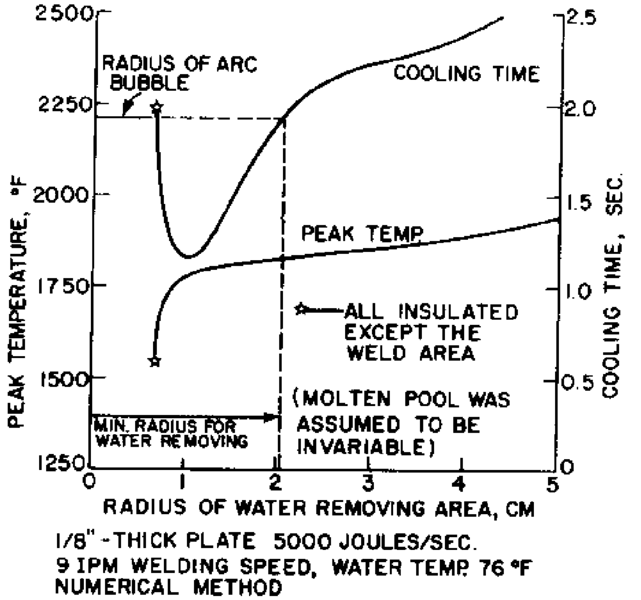


Fig. 10 – Effect of removing water on the peak temperature and cooling rate (800 to 500°C) at a point 1 mm from the fusion line on plate surface.

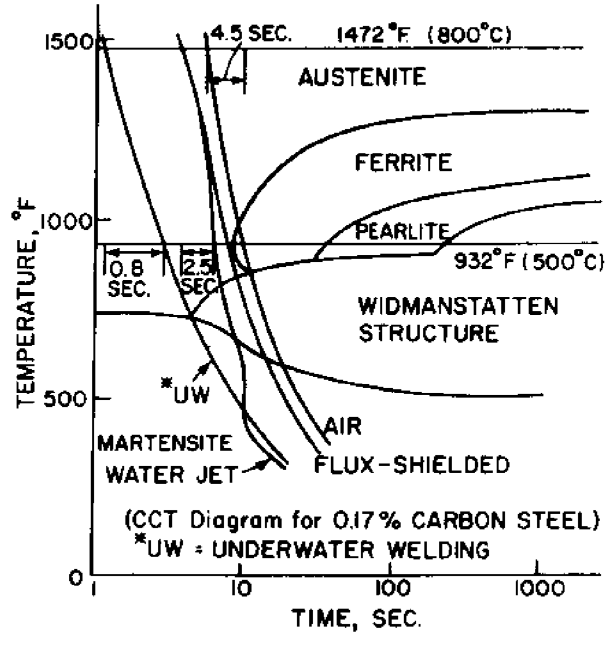


Fig. 11 – Effect of various insulation methods on cooling rate in the HAZ in underwater welding.

Mechanisms of Rapid Cooling

The rapid cooling phenomena in underwater welding is the result of surface heat losses in the weld area behind the arc. Heat is conducted into the surrounding water, which is carried up by the shear force along the interface between the water and the rising gas column. A linear correlation on a log-log scale obtained by semiempirical method explains the physical phenomena.

Use of the Arc Process in Underwater Welding

1. A change of arc power in the normal welding condition in underwater welding would not reduce the cooling problem effectively in welding a thin plate. However, the highest possible welding current is recommended for welding a thick plate.
2. Welding speed greatly affects the cooling rate in the HAZ. Slow welding speed can reduce the cooling rate effectively. Welding as slow as possible under water within the economic feasibility limit would reduce the cooling problem to some extent.
3. For thin plates, increasing the arc power does not affect the cooling rate. However, it reduces the cooling rate when the plates become thicker. High current condition is recommended when welding a thick plate underwater.
4. The direct effect of water temperature on the cooling rate in underwater welding is not dominant. Any indirect connections through the change of the molten pool require further study.

Modifications by Gases and Slags in Underwater Arc Welding

Water-Jet Process. If local water removal is necessary, the minimum radius of this dry spot must be greater than 2 cm. If a water jet is used, the postcooling effect may result in a higher hardness in the HAZ.

Hydro-Weld Process. The hydro-weld process performs the same function of removing water from the weld area. The size of the hydro-box should be kept as small as possible, but large enough to cover the entire bead and its vicinity, to ensure mobility of welding operation.

Flux-Shielded Process. A thick flux covering over the weld bead area can reduce the cooling in the HAZ effectively. Use of high-slag-formation electrodes for underwater wet welding is recommended. An addition of a flux blanket is one way to provide a heavy flux covering over the bead during underwater welding. Slag-removing tools are necessary to remove the slag completely before laying the subsequent layer in multipass welding.

Nomenclature

A = unit area
b = width of the weld bead
d = plate thickness
e = bubble height
E = arc voltage
f_{bubble} = bubble-growth frequency
g = acceleration of gravity
$\bar{h}$ = average boundary heat-loss coefficient
$h_{\max}$ = height of a departing bubble
h_T = heat-transfer coefficient
I = welding current
$\bar{k}_h$ = average thermal conductivity
L_v = latent heat of vaporization of water
$\dot{m}_f$ = mass decomposition rate of the flux
p = pressure
q = volume flow rate of bubble mixture
Q_v = heat-input rate used to vaporize water
r = bubble radius
r_c = bubble contact radius on the plate surface
$r_{\max}$ = radius of a departing bubble
r_o = radius of stable bubble void on the plate surface
R_g = gas constant of decomposed gas
R_v = gas constant of water vapor
S = size of weld HAZ
t = time
T = temperature
T_o = water temperature
T_w = plate-surface temperature
v = welding travel speed
w = heat-input density
x,y = horizontal dimensions in physical plane
α = average thermal diffusivity
ξ = moving coordinate in the welding direction

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APPENDIX

New Trend in Underwater Welding Process

The common approach to solve the rapid cooling problems in underwater welding is to remove water from the arc and its vicinity. Three underwater welding processes (hydro-weld, double-shielding, and flux-shielding techniques) adopt the same principle of water removal. They either are being used or are in the final stages of development.

Hydro-Weld Techniques

The hydro-weld process uses a highly developed gas metal-arc welding unit and a small hydro-box tailor-made to fit over the weld and the diver's hand holding the welding gun. Water is displaced from the box with inert gas, usually argon, during welding.

According to the water-removing theory, it is conceivable that hydro-weld process can provide no more rapid quenching of the weld than in air. The disadvantages of such a process are geometric restrictions and economic feasibility. However, it appears to be an attractive alternative as it combines better flexibility of operation with better quality results than those obtained in a dry hyperbaric welding.

Double-Shielding Technique

The principle of this dual shielding technique is to use the partial sealing effect of an annular water jet impinged on a flat solid surface. This technique consists of a circular shielding nozzle, which provides a stable gaseous zone around the arc by shielding the inner gas and improves the gas shielding effect underwater.

It is apparent that the size of the localized dry spot along with the joint geometry will influence the cooling behavior of the weldment greatly. The circular water jet should be large enough to include the critical area around the molten pool and to minimize the adverse effect of impinging water. On the other hand, the jet nozzle itself should be small enough to allow flexible manipulation of the welding torch.

Flux-Shielded Technique

Submerged arc welding has been used widely for surface welding to improve the quality, consistency, and welding speed. When this technique is applied for underwater, different concerns may be noted. To shield the arc and its vicinity by liquid flux, instead of the conventional gas shielding, a satisfactory welding may result if water can be prevented completely from contacting the arc and the molten puddle.

In this process a consumable electrode is fed onto the weld zone at a controlled rate while a continuous blanket of molten flux shields the weld zone from contamination, enabling the use of this process underwater. Because water is eliminated from the arc area during welding, the water-quenching rate is reduced.

SI Metric Conversion Factors

Btu × 1.055 056 E+03 = J
°F (°F−32)/1.8 = °C
in. × 2.54* E+00 = cm

*Conversion factor is exact.

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