DEVELOPMENT OF FULLY AUTOMATED AND INTEGRATED ("INSTAMATIC") WELDING SYSTEMS FOR MARINE APPLICATIONS

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ABSTRACT

This is the final report of a two-year research program entitled "Development of Fully Automated and Integrated ("Instamatic®") Welding Systems for Marine Applications". The objective of this research program from July 1, 1980 through June 30, 1982 was to develop fully automated and integrated systems. These systems package many operations involved in welding, including feeding the electrode, manipulating the torch, etc., through careful engineering, so that the welding system can be operated by a person with no welding skill. These systems have been nicknamed "instamatic®" welding systems, since they are similar to the easy to operate "instamatic®" cameras. Following a general discussion on the development of the concept of the instamatic® welding systems, discussions are given on two types of systems which have been built and tested: underwater stud welding systems, and those using arc processes. Discussions are also given on possible uses of the automatic welding systems.

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TABLE OF CONTENTS

1. INTRODUCTION

A two-year research program, "Development of Fully Automated and Integrated ("Instamatic®") Welding Systems for Marine Applications", was carried out at the Massachusetts Institute of Technology from July 1, 1980 through June 30, 1982. The objective of this research program was to develop fully automated and integrated welding systems, which package many operations involved in welding so that certain prescribed welding jobs can be performed by a person with no welding skill. They have been nicknamed "instamatic®" welding systems, since they are similar to the easy-to-operate cameras. In many cases, welding can be performed in a completely enclosed system so that no spark and very little fume are generated from the welding system. These welding systems can be successfully used for various applications, some of which are listed below:

(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 an explosion.
(3) Certain welding jobs which must be performed in a hazardous environment, where it is difficult or impossible for them to be performed by human welders.

This is the final report of the two-year research program.

2. M.I.T.'S RESEARCH EFFORTS ON UNDERWATER WELDING

Since 1968, researchers at M.I.T., under the direction of Professor Koichi Masubuchi, have conducted systematic research on underwater welding. Most of these efforts have been supported by the Office of Sea Grant, National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce through the M.I.T. Sea Grant Office. Research efforts have been carried out under the following projects:

1. "Fundamental Research on Underwater Welding and Cutting", July 1971 through June 1974.
2. "Development of New, Improved Techniques of Underwater Welding", July 1974 through June 1976.
3. "Development of Joining and Cutting Techniques for Deep-Sea Applications", July 1976 through June 1980.
4. "Development of Fully Automated and Integrated ("Instamatic®") Welding Systems for Marine Applications", July 1980 through June 1982.
5. "Underwater Welding and Cutting by Remote Manipulation Techniques", a three-year project which started in July 1982.

Results of the first three projects have been reported in M.I.T. Sea Grant Reports published in 1974, 1977, and 1981. This is the final report of the fourth project.

The research efforts were mostly done by students, mainly graduate students as their theses studies toward B.S., M.S., Ocean Engineer, and Ph.D. degrees covering various related subjects. To date, twenty-two theses and student reports have been prepared, most of which are theses toward M.S. and Ocean Engineer degrees. They are listed in Section A of REFERENCES as [T1] through [T22]. A number of reports and papers have been published. Two U.S. patents have been granted, and an application foranother patent has been filed. Names of authors and titles of important publications and patents are listed in Section B of REFERENCES as [P1] through [P26] in the order of their dates of publication. Publications [P9], [P13], and [P19] are the above mentioned M.I.T. Sea Grant Reports published in 1974, 1977, and 1981, respectively. Section C of REFERENCES lists references which are not related to the M.I.T. studies on underwater welding. They are listed as [C1], [C2], [C3], ..., in the same sequence as they are referred to in this report.

3. EXECUTION OF THE PROJECT AND PUBLICATION OF RESULTS

3.1. Execution of the Project.

This two-year research project from July 1, 1980 through June 30, 1982 consisted of the following tasks:

Task 1: Background Study and Market Survey
Task 2: Development of Initial Design of Various Types of Instamatic® Welding Systems for Marine Applications
Task 3: Construction and Testing of a Few Selected Models
Task 4: Improvement of the First Models and Design and Construction of Additional Models
Task 5: Testing of Models Constructed in Task 4
Task 6: Development of Final Design
Task 7: Preparation of the Final Report.

This research project was carried out basically as originally proposed. After Tasks 1 and 2 were performed, however, it was decided that further efforts for developing actual hardwares be done on two systems, one using arc stud welding and the other using arc welding, mainly gas metal arc welding. Mr. David Schloerb, who received an M.S. degree in Mechanical Engineering in January 1982, studied the arc stud system which can work under both dry and wet conditions. Mr. Harry Gustin, who received an M.S. degree in Mechanical Engineering in January 1982, studied the arc welding system. Experimental verifications, however, have been limited to the dry condition, although the systems may be used, with some modifications, for underwater wet welding.

A group of students at the Sloan School of Management, including Mr. Joseph F. Geary, Mr. Fred D. Johnson, Jr., Mr. Lars O. Lindgren, and Ms. Pamela A. Reid, developed a plan for a market survey on underwater arc stud welding guns as a partial fulfillment of Subject 15.828, Marketing New Products, during the first term of the 1982/83 academic year. [T21] Mr. Brian M. Leibowitz also conducted a study to evaluate the M.I.T. arc welding instamatic® system as a partial fulfillment of Subject 3.36J/13.17J, Welding Engineering, during the first term of the 1982/83 academic year. [T22] These efforts which were performed after the official termination of the research project, were done at no cost to the research contract.

3.2. Publication of Results.

Fortunately, results of this research project have been well publicized, as follows:

(1) Theses. Details of the results obtained by Mr. Schloerb were included in his thesis, "Development of a Diver Operated Underwater Arc Stud Welding System".[T19] The results obtained by Mr. Gustin were reported in his thesis, "Cartridge-Based Packaging of Automatic Welding Systems".[T20]

(2) Offshore Technology Conference. A paper, "Development of Fully Automated and Integrated ("Instamatic®") Welding Systems for Marine Applications" was presented at the 1983 Offshore Technology Conference.[P25] This paper, which is included in this report as APPENDIX A, summarizes the work conducted in this research project.

(3) International Conference on Behavior of Off-Shore Structures. A paper entitled "Automation in Underwater Welding" was presented at the Third International Conference on Behavior of Off-Shore Structures, held at M.I.T. in August 1982.[P21] This paper, which is included in this report as APPENDIX B, discusses the automatic underwater welding systems developed in this research project. The paper also briefly mentions the new research project currently underway at M.I.T. on underwater welding and cutting by remote manipulation techniques. Professor Masubuchi and Dr. Papazoglou were asked by the editor of the Offshore Magazine to write another paper based on the paper presented at the M.I.T. Conference held in August 1982. A paper entitled "Automation Introduced to Underwater Welding" appeared in the February 1983 issue of Offshore.[P23] A paper entitled "Automating Underwater Welding", which appeared in the May 1983 issue of Ocean Industry, was prepared by the editors of the Ocean Industry Magazine.[P24] The M.I.T. research has been cited as one of the seven important research papers on ocean engineering presented in 1982.

(4) International Conference on Underwater Welding. The International Conference on Underwater Welding was held in Trondheim, Norway, June 27-28, 1983 as a part of the 36th Annual Assembly of the International Institute of Welding. A paper entitled "Technology and Practices of Underwater Welding", prepared jointly by Professor K. Masubuchi, Mr. A.V. Gaudiano of Taylor Diving and Salvage Company, and Mr. T.J. Reynolds of Sea-Con Services, Inc., was

presented as one of three major survey papers.[P26] Among other subjects, this paper discusses briefly the automatic underwater welding systems developed at M.I.T. during this research project.

Since these publications are read by a large number of people who are engaged in a wide range of activities related to ocean and welding engineering, we believe that the work conducted at M.I.T. on the development of fully automated and integrated welding systems is well-publicized.

4. SUMMARY OF THE RESEARCH RESULTS

Since two theses and several papers have been prepared covering various aspects of the results generated in this research project, only a brief summary of the research results is presented in this final report. Discussions are given under the following headings:

(1) Development of the Concept of "Instamatic®" Welding Systems

(2) Underwater Stud Welding Systems

(3) "Instamatic®" Arc Welding Systems

(4) Possible Uses of "Instamatic®" Welding Systems.

4.1. Development of the Concept of "Instamatic®" Welding Systems.

Arc welding processes, including shielded metal arc (SMA), submerged arc, gas tungsten arc (GTA), and gas metal-arc (GMA) processes, are widely used for fabricating metal structures, including ships, bridges, pressure vessels, and pipelines. Most welding operations are done manually by skilled welders. Even automatic welding machines are operated by workers specially trained for the job. In most welding jobs performed on land, it is assumed that qualified welders and trained operators are always available. This assumption is usually valid when welding fabrication is performed in shipyards and other plants.

Likewise, underwater welding operations are almost exclusively done manually at present (refer to APPENDIX B, page 758). Again, arc welding processes, included SMA, GTA, and GMA processes, are most widely used. However, M.I.T. researchers believe that it is quite possible to introduce automation in underwater welding for improving the weld quality and reducing fabrication cost. In fact, welding automation is essential in developing underwater welding technologies in deep sea.

The basic concept of "instamatic®" welding was developed by M.I.T. researchers during an early study on joining and cutting techniques for deep-sea application.[P19] In fact, the word "instamatic®" was used in the Sea Grant Report published in 1981. In order to successfully accomplish welding fabrication and repair in deep sea, it is important to package some operations involved in welding, including feeding the electrode and manipulating the torch so that very little skill is needed to perform the welding jobs. Development of such fully automated and integrated systems are desirable for the following reasons[P25]:

(1) It is difficult to obtain a sufficient number of workers who are qualified in both diving and welding, particularly for underwater welding jobs performed away from cities and/or in deep sea.

(2) Because deep sea welding must be performed under severely adverse conditions, even a qualified diver/welder may not be able to perform high-quality welding jobs.

Any mechanical devices which simplify the work that must be performed by the diver/welder should help to improve the quality of the work and reduce construction costs.

Sometimes the development of one new concept leads to the development of several new and varied applications of that concept. In this case, M.I.T. researchers realized that similar systems to that described above can be developed for a number of applications other than deep sea welding. In fact, underwater systems, especially those which must operate in deep sea, are far more complex than the development of similar applications for a dry environment. The research at M.I.T. towards an "instamatic®" welding system has led to a novel concept of using an enclosed welding system, which is a radical departure from the current practice of welding fabrication.

Currently, pieces to be welded are first assembled together, and a welder or welding machine comes to the weld location to perform the welding. By contrast, the new system contains the piece to be welded in a "cassette" similar to a cassette tape installed in a tape recorder, or a cartridge-type film installed in a Polaroid® camera. This new concept is based on a cartridge welding device which automatically performs the desired welding by pushing just one button to activate the device.

One obvious restriction of this new approach is that such a system can perform only those jobs which have been predetermined for the system. However, we believe that by properly selecting joint geometries commonly used, a series of "instamatic®" welding systems can be developed which can perform a considerable percentage of the welding jobs needed in actual construction. The objective of Task 2 of this research project was to determine several joint designs which are simple enough to be constructed during this research project and yet have relatively broad applications. Some of the joint examples identified for using the instamatic® welding systems are as follows (see Figure 1):

(a) Stud welding a bar to a plate, as shown in Figure 1a. Further discussions are given in a later part of this report.

(b) Stud welding a bar to a pipe, as shown in Figure 1b.

(c) Joining a flat plate to a plate by fillet welding, as shown in Figure 1c. Further discussions are given in a later part of this report.

(d) Joining a pipe to a plate by fillet welding, as shown in Figure 1d.

(e) Lap welding a cover plate to a flat plate, as shown in Figure 1e.

(f) Replacing a section of a pipe, as shown in Figure 1f.

Various other types of "instamatic®" welding systems can be conceived and developed.

The basic technologies and machine components needed for the construction of "instamatic®" welding systems are rapidly expanding today as follows: [P25]

(a) In the welding industry there is a surge of interest in the increased automation and miniaturization of welding machines and tools utilizing modern electronics technologies. Some welding machines and power supplies using solid state devices are very small. Some of them can even be operated by the ordinary 110-volt electric outlet available at home.

(b) There has been a tremendous increase in the use of robots in welding and other manufacturing processes. Some components of these robots can be used as parts of "instamatic®" welding systems.

(c) Many newly developed machines and tools are very "smart", since they are equipped with various types of advanced sensing and control devices. At present, there is a strong interest in developing "smart" welding machines which have adaptive control capabilities. Until recently, all automatic welding machines have performed welding using predetermined welding conditions, with no adaptive control in process. However, M.I.T. researchers, under the direction of Professor Masubuchi, have been working

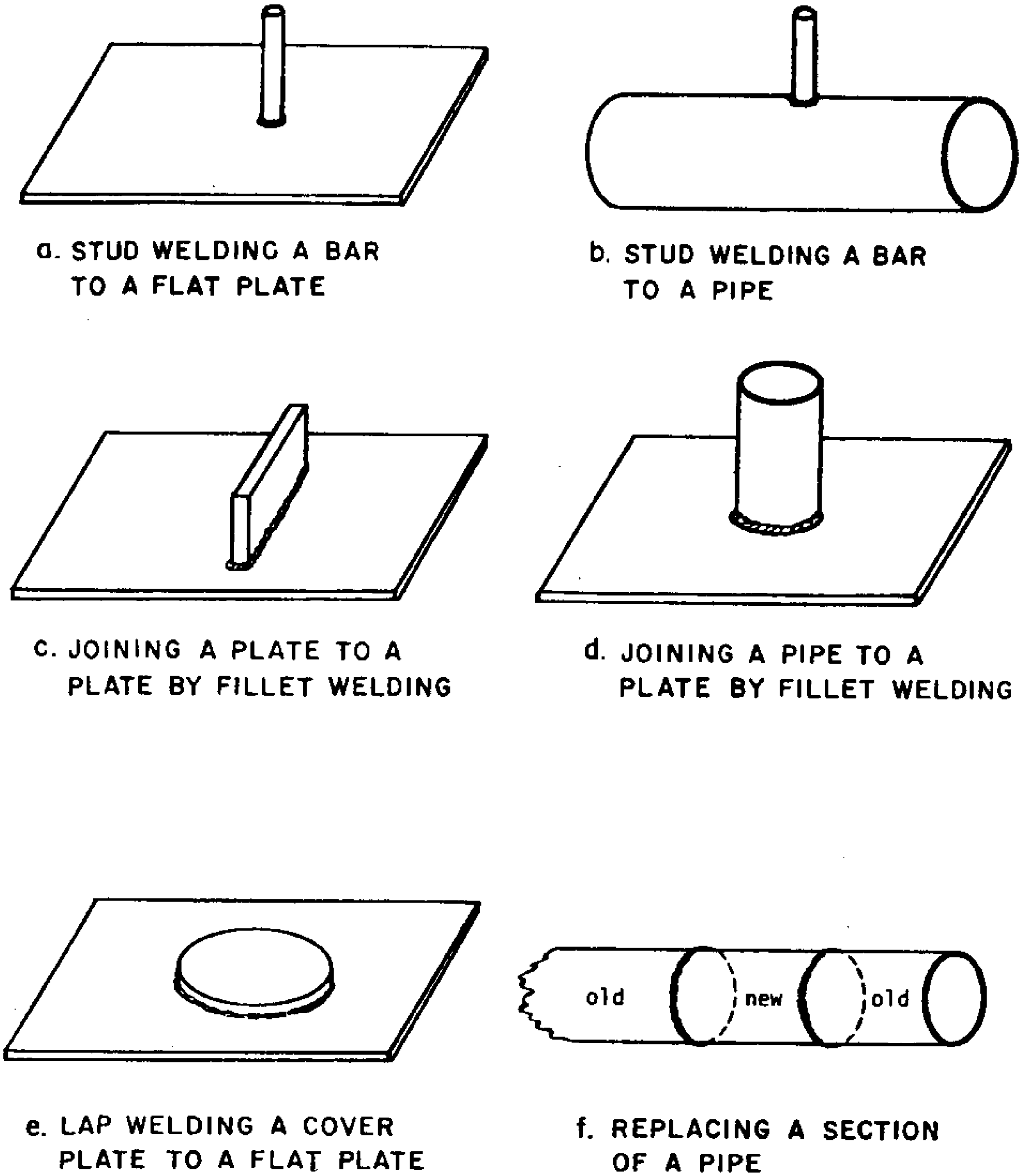


FIGURE 1 Several basic joint types investigated for welding by "instamatic"® systems

on a research program for developing "smart" welding machines for the girth welding of pipes.[C1]

On the basis of the current technology of automatic welding machines, we believe that simple automatic welding machines with no adaptive controls are probably good enough for a number of "instamatic®" welding systems. However, more sophisticated machines which have adaptive control capabilities will be needed for other applications such as the welding of stationary pipes. In welding a stationary pipe, welding conditions change as welding progresses and the welding position changes. In order to successfully weld a pipe in all positions, a machine probably needs in-process sensing and control capabilities, or it must at least have a capability for changing welding conditions as the welding progresses in a pre-determined fashion. Some degree of smartness may be needed in welding machines to be used in "instamatic®" welding systems.

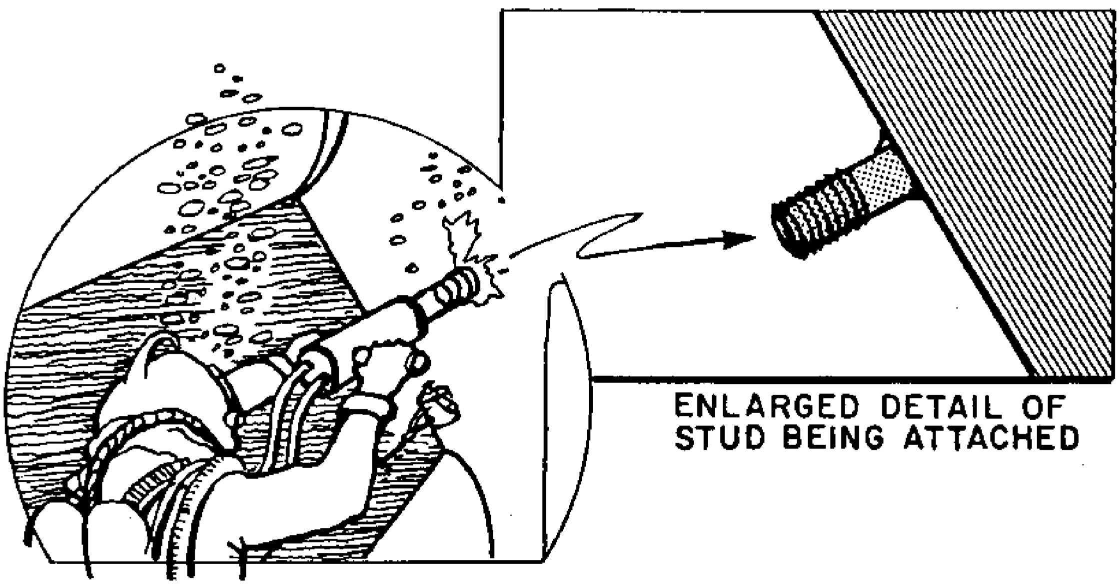
4.2. Underwater Stud Welding Systems.

Stud welding on land has been used since the 1930's.[C2] The first recorded underwater stud welding field tests occurred in 1944.[C3] Stud welding in air has found wide applications wherever the attachment of a large number of studs is required. A variety of stud shapes, sizes, and materials have been successfully employed.[C4]

Conventional stud welding equipment consists of a stud gun, an electric controller, and a D.C. power source. To make a weld, the operator simply loads a stud into the gun, presses it against the work surface, and pulls the trigger. The electric controller then controls the sequence of the welding process according to predetermined settings.

Stud welding can be classified into two basic types, depending upon the type of power source used. The first type, capacitor discharge stud welding, employs a bank of charged capacitors as the power source. Because of the extremely short weld time associated with this technique, on the order of milliseconds, capacitor discharge stud welding is inherently limited to studs smaller than approximately 1/4 inch in diameter. On the other hand, the second type of stud welding, known as arc stud welding, can weld studs of more than one inch in diameter.

Because of the simplicity of this process and the ready availability of conventional land stud welding equipment, M.I.T. researchers have been interested in underwater uses of stud welding since 1974. Underwater stud welding also has been studied by investigators in other countries including France, Japan, and the Netherlands.(C5-C8) In fact, stud welding may be the only process, other than arc welding processes, which have been used to some extent for actual construction underwater.[P26] COMEX Services in France and several other companies have used stud welding for some underwater construction and other repair works.(C7) Figure 2 shows schematically how a steel stud may be attached to an underwater structure.



NOTE: This figure has been drawn based on the information given in an article prepared by COMEX Services(C7)

FIGURE 2 Schematic figure showing how a steel stud may be attached to an underwater structure[P26]

Research on underwater stud welding at M.I.T. was first conducted in 1974 by Zanca,[T8] who developed a prototype capacitor discharge stud welding gun for underwater use. A U.S. patent on an underwater welding gun was granted to Masubuchi and Kutsuna.[P11] It was decided that the research effort on stud welding be expanded to be able to weld larger stud by using arc stud welding. The first research effort at M.I.T. on underwater arc stud welding was made in 1976 by Chiba. Details of his research are described in his thesis[T12] and the M.I.T. Sea Grant Report published in 1981.[P19] A brief summary of his work is presented below.

Chiba welded steel studs in shallow, one inch deep water using an experimental set-up as shown in Figure 3. Mild steel studs, 3/4 inch in diameter, were welded to 1/2 and 1 inch thick plates of mild steel and HY-80 steel. HY-80 is a quenched and tempered steel with the specified minimum yield strength of 80,000 psi. HY-80 steel has been widely used for pressure hulls of U.S. Navy submarines. Good quality welds were obtained in both air and underwater welding.

Chiba found that most stud welds made in the air and underwater performed satisfactorily in both tensile and bend tests. In most case, fractures occurred at the threaded portion of the stud. Examinations of metallurgical structures and hardness were made on several specimens on a cross section, as shown in Figure 4. An interesting observation was that the maximum hardness obtained in the heat-affected zone in the base metal (location 4 in Figure 4) was little affected by the presence of water. This can be explained as follows: cooling rates of regions near the outer surface of the stud are affected by the presence of water; however, those in regions near the center of the stud are little affected by the presence of water.

We believe that stud welding is more fundamentally suited for underwater wet welding, when compared with other welding processes, such as shielded metal arc welding. In wet shielded metal arc welding, molten metal from the electrode must be transferred in small particles

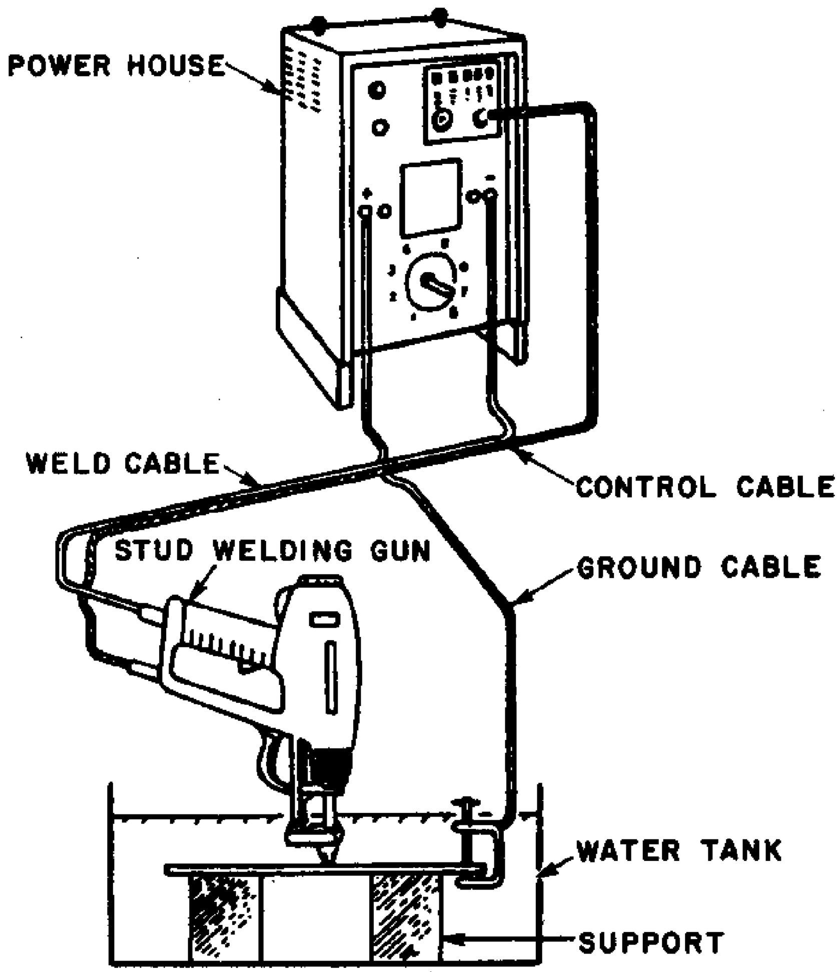


FIGURE 3 Arc stud welding setup used by Chiba [P19]

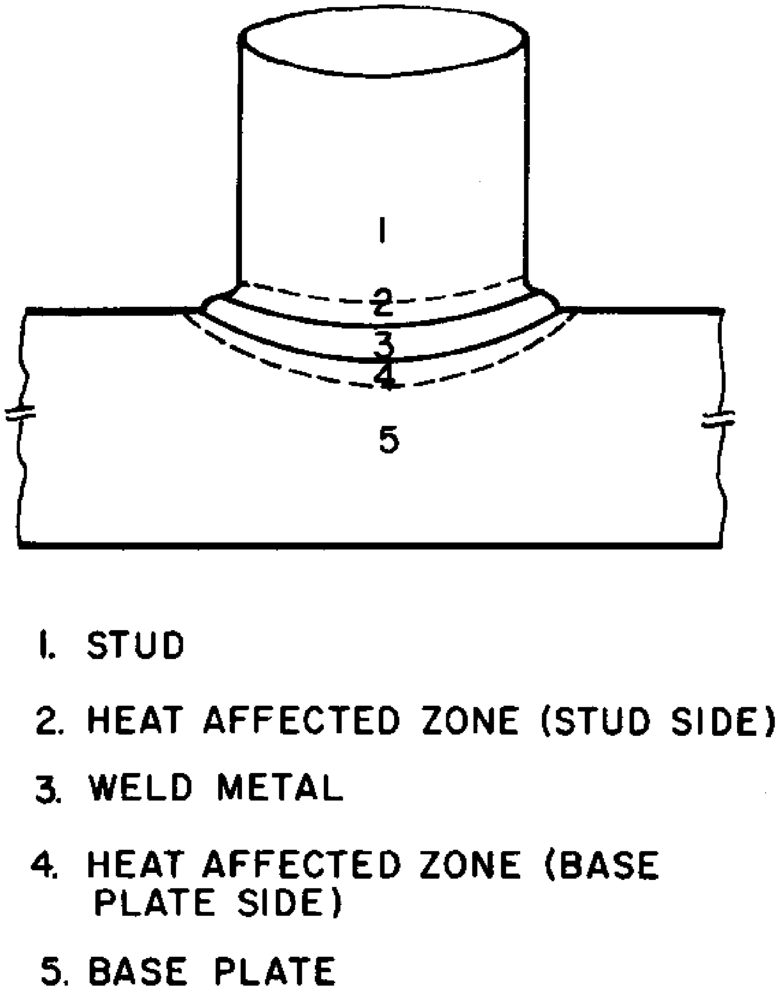


FIGURE 4 Cross section of a stud welded joint

travelling in the arc atmosphere surrounded by water. As the arc moves, the weld metal is exposed to a large mass of water which has a tremendous quenching effect on the weld. On the other hand, in the case of stud welding, metals in the central portions of the stud are very little affected by the presence of water, if the small amount of water that existed between the stud and the base metal is squeezed out from the weld region when the stud is pushed against the base plate, toward the end of the welding operation.

Kataoka continued the study on underwater arc stud welding. Details of Kataoka's work are described in his thesis[17] and the M.I.T. Sea Grant Report published in 1981.[P19] The stud welding gun and test specimens were placed in a pressure tank to simulate dry and wet welding in deep sea. Kataoka found that increased pressure caused the arc to bend and become unstable. He was able to produce "good quality" welds with 1/2 inch diameter studs in air and water up to a pressure of 50 psig.

Encouraged by the successes achieved by Chiba and Kataoka, Schechter[T18] made an effort to develop a stud welding gun which could be completely immersed in water. In previous studies by Chiba and Kataoka, tests had been made with the work surface horizontal, because the gun used in the tests could not be allowed to get wet. Schechter determined that the gun should (and could) be designed to be "water-floodable" rather than waterproof. This idea, which was originally suggested by Mr. Charles Parker of the M.I.T. Stroboscopic Laboratory, is based on the fact that it is much easier to make the working mechanism of the gun so that it could be immersed in water, than it is to try to keep the water out. Schechter also designed a flexible ferrule mounting which made it possible to make good welds even when the stud welding gun is not held exactly perpendicular to the work surface. In underwater welding, it is rather difficult to position the welding gun exactly perpendicular to the work surface.

Schloerb[T20] picked up where Schechter left off. In particular, Schloerb decided to construct a fully submersible arc stud welding gun. His further goal was to develop a practical system which could be tested in the field. Schloerb, who has diving skill, decided that the welding system should be diver-operated. Naturally, a diver-operated system is not the only approach. Indeed, a remotely operated system would have a significant advantage in the deep sea. However, the development of a diver-operated system was felt to be of immediate practical benefit to the industry. Efforts are currently being made to further develop stud welding systems which could be remotely operated from an underwater vehicle.

Schloerb's work is detailed in his thesis.[20] A paper presented at the 1983 Offshore Technology Conference describes, among other subjects, a summary of Schloerb's work.[P25] A short summary of his work, based mainly on the OTC paper, is given below.

A prototype of the underwater stud system was constructed, and a number of developmental tests were performed. Figure 5 is a schematic diagram of the final design by Schloerb. Key features of the gun are shown.

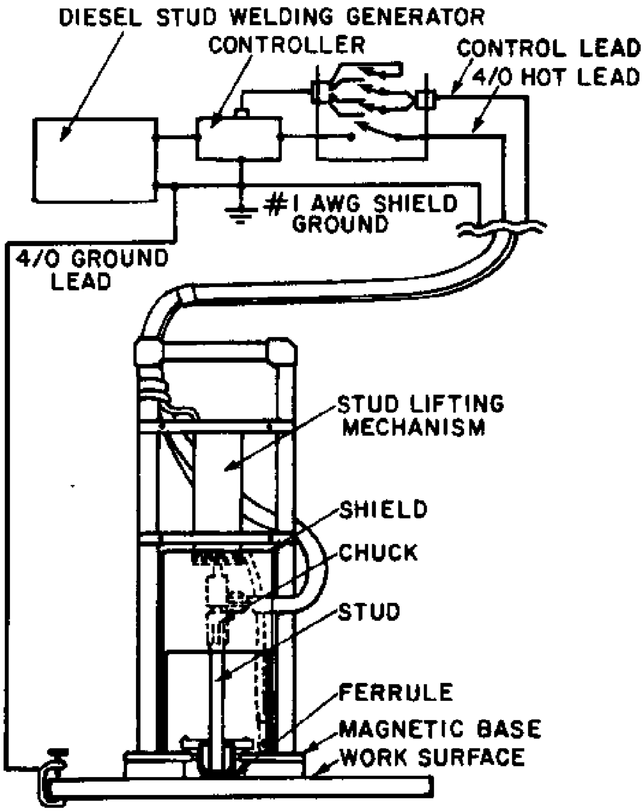


FIGURE 5 Diver-operated arc stud welding system developed by Schloerb[T20, P25]

The system incorporates a conventional diesel stud welding generator and a conventional electronic controller which are located out of the water. The trigger switch, which initiates the weld cycle, is also located on the surface for safety reasons. This switch is incorporated in a knife switch which assures that electrical power to the stud gun is only on when a weld is actually being made. The knife switch is operated by the diver's tender on command from the diver. An electrical umbilical connects the surface equipment to the submersible arc stud welding gun.

The heart of the stud gun is the stud lifting mechanism. This mechanism lifts the stud a predetermined distance in order to produce a precise arc gap between the end of the stud and the work surface. The arc gap is adjusted by moving the lift mechanism along the support framework.

The force to lift the stud is generated by a solenoid which is activated by the control unit. The control unit initiates the welding arc at the same time as the stud is lifted. The arc causes the end of the stud and a portion of the work surface to melt. After a predetermined time, the control unit stops the arc and de-energizes the solenoid. At this point, a spring forces the stud back against the work surface. A disposable ceramic collar, called a ferrule, is held in place around the base of the stud to prevent weld splatter. The molten metal solidifies quickly leaving the stud welded to the work surface.

The system employs conventional ferrules and a conventional ferrule clamp. The ferrules are press-fit on the ends of the studs, using steel wool prior to the dive in order to make it easier for the diver to handle them. The steel wool also serves as an arc initiator.

Considerable work has been done to make the entire system as simple as possible. As a result, the lifting mechanism has only one moving part--the lifting rod which transmits force to the stud. Another key feature is the fact that the lift mechanism is "water-floodable" rather than waterproof. A plastic case prevents electrolysis of the lift mechanism components and helps to reduce the extent of the electric field which surrounds the gun.

During the thesis research, which had a major objective of developing an underwater arc stud welding system, Schloerb became concerned with the safety of a diver/welder against electrical shock. He decided to investigate the electrical field in the water around the stud welding gun. Preliminary calculations anticipated that this field would present a hazard for the diver who is operating the gun. This was confirmed by measurements which found the magnitude of the electrical field near the gun to be more than 100 times the recommended safe limit. A conventional underwater welding stinger, on the other hand, was found to produce a field whose magnitude was just equal to the safe limit.

It has been proposed that a grounded aluminum shield, placed around the stud, could be used to reduce the field to a safe level. Development of the shield is not complete. A preliminary shield design was found to reduce the magnitude of the electric field by a factor of 20.

In addition to the components described above, the stud gun consists of the following basic parts: a chuck holder, which adapts to conventional stud welding chucks, connects the lifting rod to the stud and serves as the "hot" electrical connection; and a permanent magnetic base employed to hold the gun in place during the welding operation. The base will attach to both flat and cylindrical surfaces.

A patent application has been filed on an invention entitled "Diver-Operated Underwater Arc Stud Welding Systems".[P21] Additional efforts are being made to further improve the underwater arc stud welding system under the new research project on remotely manipulated welding.

4.3. "Instamatic® " Arc Welding Systems

Initial work for the development of "instamatic® " welding systems using arc welding processes was performed during an earlier research project on joining and cutting techniques for deep-sea applications.[P19] Lombardi[T19] worked on the development of an enclosed unit for underwater welding using the flux-shielded process. In fact, his study followed earlier studies by Tsai[T13] and Erickson[T15]. Tsai, who was studying methods for preventing rapid quenching of underwater wet welds, thought that submerged arc welding might be a good process to be used underwater since the weld metal is covered by a flux. Masubuchi and Tsai[P15] obtained a U.S. patent on underwater submerged arc welding. Erickson[T15] then studied effects of pressure on flux-shielded arc welding underwater.

Figure 6 shows the conceptual design developed by Lombardi of an enclosed unit for underwater welding using the flux-shielded process. This system is used to attach a plate to a flat plate by fillet welding, as shown in Figure 1c. Details of the work by Lombardi are described in his thesis[T19] and the M.I.T. Sea Grant Report published in 1981.[P19]

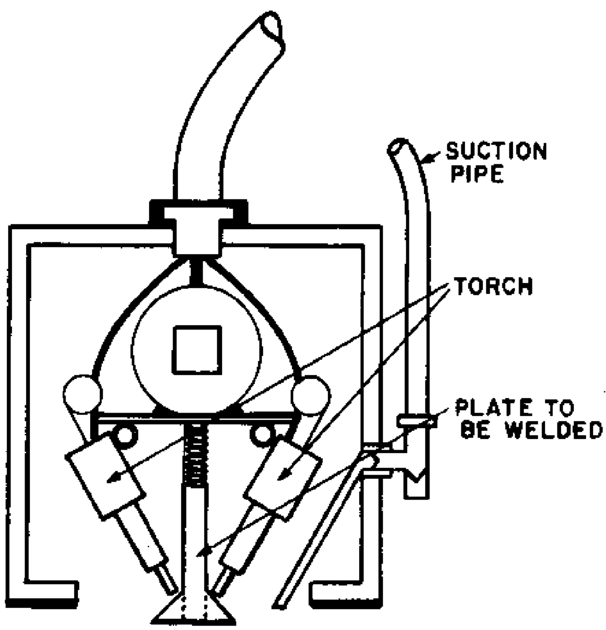


FIGURE 6 Conceptual design of automatic underwater welding machine developed by Lombardi[T19, P19, P25]

Lombardi built a prototype and tested it in air. A unique feature of this system is that welding is performed in a completely enclosed box; therefore, practically speaking, no sparks and no fume will be generated during welding. In order to use the system underwater, the entire unit shown here probably needs to be installed in a strong watertight vessel.

The machine consists of a motorized carriage which simultaneously provides the consumable electrode feed into two torches, and the wire feed speed. These electrodes are connected via cables to the power supply which is not shown here. A plate to be welded is placed securely between the torches, parallel to the line of travel. Stainless steel foil moulded 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. Figure 7a through 7f show the sequence of the operation. First, the machine is placed upon the steel object on which the welding will take place, as shown in Figures 7a and 7b. The machine is then emptied of all the water by forcing water from the surface down through a valve containing a series of pivot tubes, as shown in Figure 7c. The velocity of the water will cause the water to be sucked out of the box through the valve, creating a local dry environment. 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. Figure 7d shows the inside of the box. The arc, being of high temperature, will burn through the foil at the bottom of the box and can be maintained 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 box is then flooded and the machine removed due to the loss of suction, as shown in Figure 7e. The plate will be left welded to the metal object, as shown in Figure 7f.

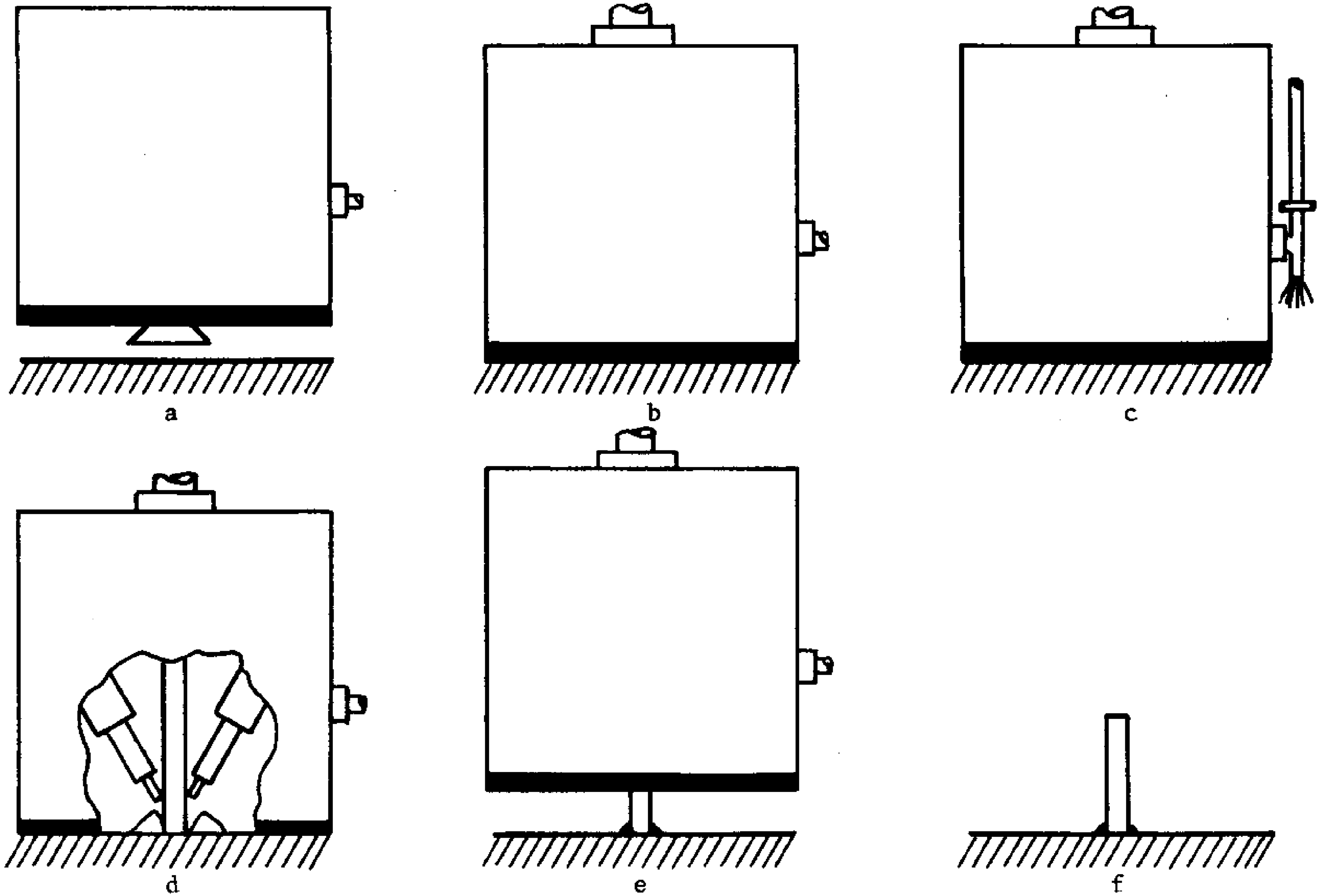


FIGURE 7 Welding procedure sequence of automatic welding machine[P19]

Gustin[T21] continued the work started by Lombardi. However, Gustin's work differs from that of Lombardi in the following ways:

(1) Gustin's work is primarily directed toward developing a machine to be used in air, while Lombardi's work was aimed at developing a machine to be used underwater;

(2) Gustin decided to use the gas metal-arc (GMA) process which is easy to control; and,

(3) Regarding the joint configuration, Gustin decided to work on lap welding a circular cover plate to a flat plate, as shown in Figure 1e. It was felt that Lombardi's work showed that an "instamatic®" welding system can be built for joining a plate to a plate by fillet welding, as shown in Figure 1c.

Gustin designed and constructed a device capable of welding a circular "cartridge" of low-carbon steel to a base plate of similar material. Figure 8 shows the schematic of the design which can be summarized as follows:

(1) A GMAW (MIG) gun is mounted on a shaft so that rotation of the shaft causes the gun to transverse the desired circular path.

(2) A cartridge holder is mounted concentrically on the shaft. The cartridge holder accepts the patch to be welded and mechanically positions the patch against the base plate. A bearing component of the cartridge holder allows the shaft to rotate without requiring holder rotation.

(3) The enclosure shown provides structural support for the other components. In addition, the enclosure provides the potential for using the device as an isolated welding system.

Commercial welding devices (e.g., power supply, shielding gas, cooling water systems, wire feed equipment, etc.) are used in conjunction with the illustrated equipment to perform the desired circular patch weld.

The designed system was tested successfully in a laboratory environment. Good quality welds were obtained, judging from their bead

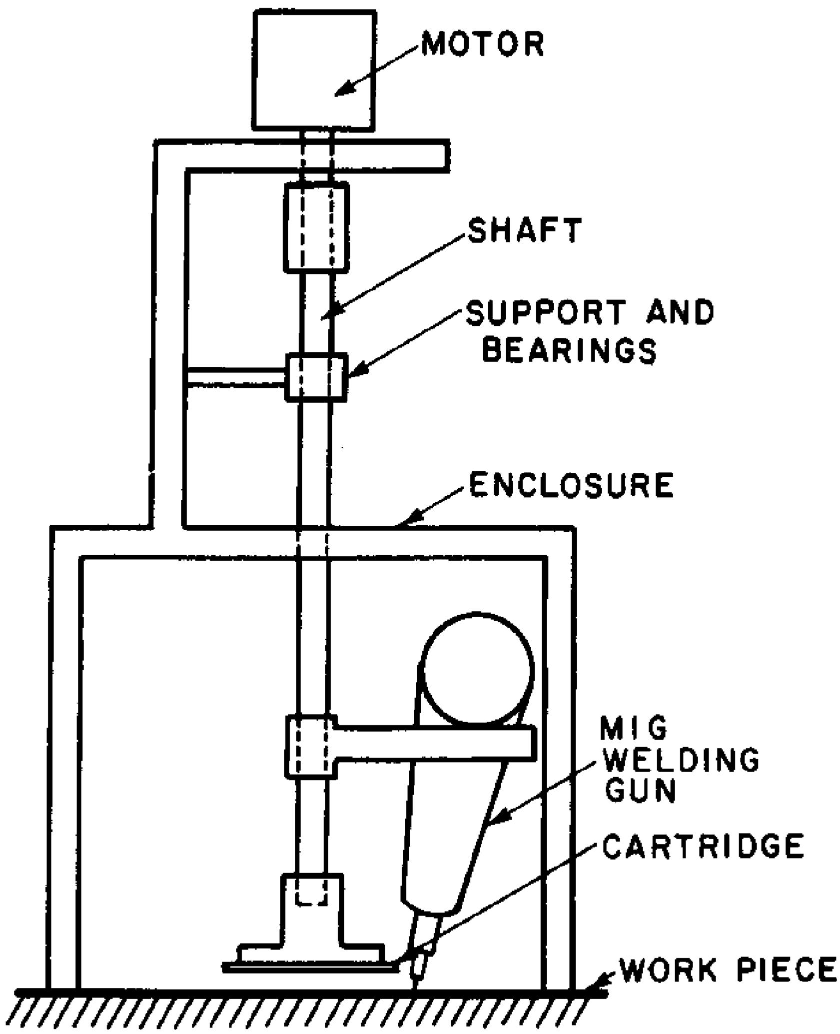


FIGURE 8 A device capable of welding a circular patch to a flat plate developed by Gustin[T21, P25]

and heat effect uniformity, good fusion characteristics, absence of any burn-through, and adequate weld penetration.

4.4. Potential Markets for "Instamatic®" Welding Systems.

In discussing potential markets for "instamatic®" welding systems, we should treat stud welding systems and cartridge-type arc welding systems separately, because they are considerably different in the complexity of the system, the degree of departure from the normal current practice, and the stage of development, as follows:

(1) The stud welding system developed at M.I.T. is a rather simple system with few moving parts. Although various efforts have been made by M.I.T. researchers to make the system workable under water, little change has been made, as far as the mechanisms of welding are concerned, over the current stud welding machines used in air. The system is well developed, and it has been tested in both air and underwater.

(2) The arc welding systems are considerably more complicated than the stud welding system, having a number of moving parts. The concept of cartridge-type welding is a very radical departure from the current practices of arc welding. Although two prototypes, one to attach a plate to a flat plate by fillet welding, (see Figure 1c) and the other to weld a circular patch to a flat plate (see Figure 1e), have been built and tested to verify that the basic idea is sound, further efforts are needed to develop and build truly workable systems. All the tests conducted thus far have been done in air.

Consequently, further discussions are given on the following subjects:

(1) Potential markets for underwater stud welding systems

(2) Potential markets for "instamatic® " arc welding systems for marine applications

(3) Potential markets for "instamatic® " welding systems (including both stud welding and arc welding) for non-marine applications.

4.4.1. <u>Potential Markets for Underwater Stud Welding Systems</u>. As stated earlier in this report, stud welding has been used to some extent for actual maintenance jobs on undersea structures. In fact, stud welding is the only process other than the arc welding process that has been used for actual work underwater, although many investigators have studied possible underwater uses of many other processes.[P26] However, underwater uses of stud welding thus far have been very limited, although the process can potentially be used for many applications. In order to accomplish increased underwater uses of stud welding, the following should be done:

(1) Develop stud welding guns which can be immersed in water. We must first have stud welding guns which can be operated safely underwater. COMEX claims that they have developed an underwater stud welding system.(C5) M.I.T. researchers have also developed stud welding systems which can be operated underwater. They are still continuing to improve their systems.

(2) Develop an integrated system which can clean the metal surface, position the gun at the right location in the right direction, make sure that welding operations are performed correctly, and then inspect the weld. In order to obtain a good weld, the metal surfaces to be joined must be clean, free of rust, barnacles, and other foreign materials. The stud must be positioned at the right location, and it must be aligned perpendicular to the surface to be welded. We must apply the right welding conditions, including welding current, arc voltage, and welding time (the number of cycles). It will be extremely useful if we have an in-process sensing and control system to ensure that welding has been performed adequately. It is also important to develop a system to inspect the weld as soon as it is made. These operations are relatively easy to do in air or land, and are often done by different people. However, it is extremely difficult and costly to have these operations done underwater. It is essential to develop an integrated and automatically controlled system, or a series of systems, to perform some or all of these operations underwater. Efforts are currently being made at M.I.T. to develop an underwater arc stud welding system which is capable of sensing and controlling welding conditions in real time.

(3) Develop recommended standard practices and/or specifications on underwater stud welding. The American Welding Society recently developed a specification on underwater welding.(C9) However, this specification includes only arc welding processes. It would be extremely helpful for increased uses of underwater stud welding if recommended

practices and/or specifications by a proper organization are established.

Potential markets for underwater stud welding are not only large but also varied. Only a few examples of possible applications are listed below:

(a) Attach studs for fixing anodes for corrosion protection to underwater stuctures,

(b) Attach studs to a variety of structures used in harbors and river banks,

(c) Attach studs to sunken objects for salvaging.

We believe that the markets for (a) and (b) are especially large.

Although almost all of underwater welding jobs (under both dry and wet conditions) are currently done manually using arc welding processes, it becomes extremely difficult and costly to perform these jobs in deeper waters.[P26] M.I.T. researchers believe that stud welding is fundamentally more suited to underwater welding jobs which must be performed in deep sea than arc welding processes because:(1) the stud welding process is likely to be less affected by the water pressure than arc welding processes and (2) it is easier to automate the stud welding process than the arc welding processes. It is feasible to develop a completely mechanized underwater stud welding system which can be operated remotely. In fact, efforts are currently underway at M.I.T. to develop an underwater arc stud welding system which can be remotely operated.

Figure 9 shows schematically an imaginary case explaining how an integrated underwater stud welding system may be used to lift a sunken object in ocean salvage operations.[P19] An unmanned remotely operated vehicle carrying an underwater stud welding system dives down to a destination on the sunken object, such as a disabled submarine. Stud welding is performed by remote control from the surface ship. Or the stud welding system may be attached to a manipulator attached to a manned submersible, and personnel on board the submersible may

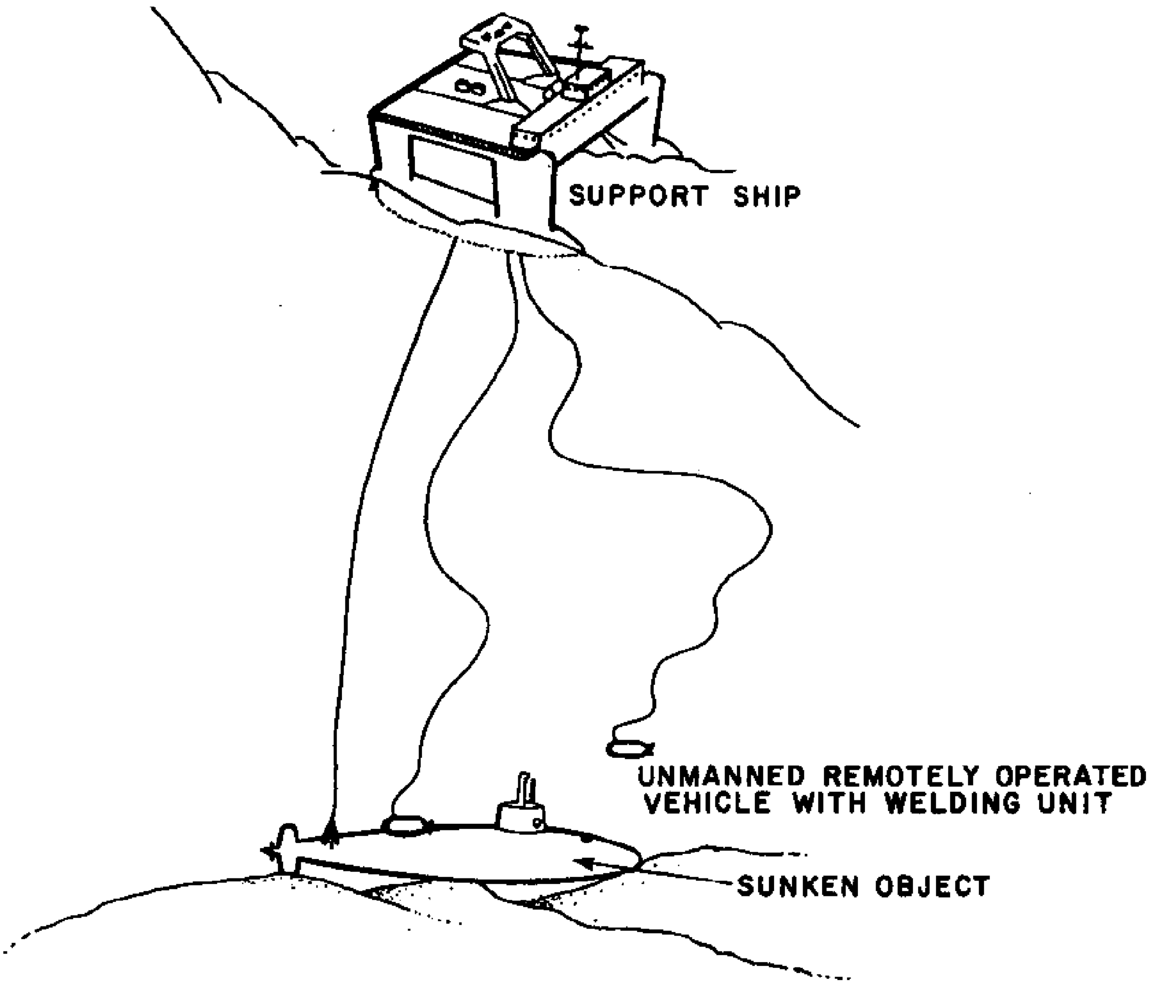


FIGURE 9 Application of an integrated underwater stud welding system for ocean engineering operation [P19]

remotely position the welding system and activate the welding operation. After welding is completed, lift ropes are attached to the stud welded unit. The vehicle moves to another location and repeats the operations. Finally, the support ship gathers the lift ropes and lifts the sunken object.

It may be worth mentioning economical problems which have inhibited the development of integrated underwater welding systems. The key to the development effort is the development of the stud welding gun and the control system. Today stud welding machines are manufactured and marketed by only a few companies including Nelson Division of TRW, Inc. and KSM Fastening Systems Division of Omark Industries. These companies have expressed considerable interest in underwater uses of stud welding. In fact, these companies have assisted the M.I.T. Research through providing equipment, materials, and advices (see ACKNOWLEDGEMENT). However, they seem to think that the market for underwater stud welding is still too small to justify a large-scale research and development effort to develop workable systems, and then manufacture and market them. There is another technical problem. Companies which have knowledge and experience with welding machines do not have knowledge and experience in diving and underwater work.

Development of underwater stud welding systems may be done through a joint effort between a salvage company and a manufacturer of stud welding machines. In fact, COMEX Services and Nelson Division of TRW worked together to develop their underwater stud welding system.[C5] The problem, however, is that the salvage company that has developed the underwater welding system is often very reluctant to disclose details of their work to potential competitors. They frequently feel that it is to their economic advantage to maintain technical secrecy, and capture the often limited market of contracting the salvage work. Some assistance from a government agency may be needed to close the gap now kept open by the constraints of market forces. One aid would be increased funding of the needed development work by the Department of Commerce. The funding could also come from the U.S. Navy, which would received significant benefit from new technology that would be very useful in their operations.

4.4.2. <u>Potential Markets for "Instamatic® " Arc Welding Systems for Marine Applications</u>. The "instamatic® " arc welding systems can be used for various applications, some of which are listed below:

(1) Certain repair jobs which must be performed either on board a commercial or military ship or on an offshore oil drilling rig when no skilled welder is available. It is important to have the capability of performing some maintenance and repair jobs without a qualified welder.

(2) Rehabilitation of steel structures, especially offshore oil-drilling rigs and other ocean engineering structures. Some of them need and will need various types and degrees of repairs. Unlike ships which can be brought to docks for repair, many repairs on offshore structures must be performed in position, including underwater. "Instamatic® " welding systems may be used for some repair jobs, primarily minor repairs.

(3) Jobs requiring attachment of various metal pieces to ocean structures. For example, the attachment of anodes for corrosion protection is a major maintenance job on ocean structures. There are many other minor jobs for attaching metal pieces with various shapes and sizes to ocean structures, for a variety of purposes. Many of these welding jobs may be done by "instamatic® " welding systems.

(4) Certain welding jobs which must be performed in hazardous environments, such as in compartments where sparks from the welding arc may cause fires or explosions. Since welding operations in an "instamatic® " welding system are performed in an enclosed box, the possibility of causing fires and explosions from welding sparks can be minimized. There are other cases in which it is difficult or impossible to perform welding using humans, such as welding in areas filled with toxic gases. "Instamatic® " welding systems, perhaps activated by remote control, may be used in these cases.

Compared to the discussions on potential market for underwater stud welding presented earlier (4.4.1), discussions on potential markets for "instamatic® " arc welding systems are less precise and more general in nature because (1) the "instamatic® " arc welding system represents a radical departure from the normal current practices of arc welding, and (2) the system has not yet been well developed. As stated earlier (4.1), the concept of having a piece to be welded in a detachable "cassette" inserted in a box containing welding torches, and then to remove the box after welding is completed, is a totally new idea. It is extremely difficult to assess how such machines would be accepted by society. The fact that there is no similar product does not necessarily mean that there will be a limited market for the new product. There have been a number of examples of new products which created or vastly increased markets after the products were introduced. They include Xerox copying machines, "instamatic® " cameras, tape recorders, and pocket electronic calculators. The key factor is how the new product can exhibit superior performances over existing products. For this reason what is most important here is to develop "instamatic®" arc welding systems which can produce high-quality welds without using skilled welders. In the current research project at M.I.T. efforts are being made to develop "instamatic® " arc welding systems which can be remotely operated. We expect, however, that tests will be performed primarily under dry conditions.

4.4.3. <u>Potential Markets for "Instamatic® " Welding Systems for Non-Marine Applications</u>. "Instamatic® " welding systems using stud welding, arc welding and other processes may be used for a variety of non-marine applications. First of all, they can be useful for welding operations which must be performed without using skilled human welders. These applications include:

(1) Repair welding of some nuclear reactor components which must be performed in the radioactive environment,

(2) Construction and repair by welding of space stations which must be performed by astronauts wearing space suits, and

(3) Construction and repair by welding of some Arctic structures which must be performed by personnel wearing heavy coats.

There may be a number of different applications in which welding must be performed: (a) under hazardous environment, (b) when skilled welders are not available, or (c) while personnel are wearing special, bulky clothing.

An M.I.T. research team, under the direction of Professor K. Masubuchi, has been recently selected by the Office of Space Science and Applications, of the National Aeronautics and Space Administration, to perform a feasibility study of remotely manipulated welding as a step toward developing novel joining technologies.[C10] This study is being conducted as a part of the Innovative Utilization of the Space Station Program. Possible uses of "instamatic® " welding systems, among other subjects, are being studied.

When "instamatic® " welding systems are well developed and they are found to be useful for other applications, they may be used for a variety of applications. However, it is too early to predict exactly how widely "instamatic® " welding systems may be used.

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APPENDIX A

OTC 4601

Development of Fully Automated and Integrated ("Instamatic") Welding Systems for Marine Applications

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ABSTRACT

A two-year research program was conducted at M.I.T. to develop fully automated and integrated welding systems. These systems package many actions involved in welding so that certain prescribed welding jobs can be performed by a person with no welding skill. They have been nicknamed "instamatic"® welding systems, since they are similar to the easy-to-operate cameras. Following a general discussion on the development of the concept of the "instamatic"® welding system, discussions are given on two types of systems which have been built and tested: underwater stud welding systems, and those using arc welding processes.

INTRODUCTION

From a modest beginning in 1968, researchers at the Massachusetts Institute of Technology, under the direction of Professor Koichi Masubuchi, have conducted systematic research on underwater welding. Most of these efforts have been supported by the Office of Sea Grant, National Oceanic and Atmospheric (NOAA) of the Department of Commerce through the M.I.T. Sea Grant Office. Research efforts have been carried out under the following projects:

1. "Fundamental Research on Underwater Welding and Cutting", July 1971 through June 1974[1]
2. "Development of New, Improved Techniques of Underwater Welding", June 1974 through June 1976[2]
3. "Development of Joining and Cutting Techniques for Deep-Sea Applications, July 1976 thorough June 1980[3]
4. "Development of Fully Automated and Integrated ("Instamatic")® Welding Systems for Marine Applications", July 1980 through June 1982[4]
5. "Underwater Welding and Cutting by Remote Manipulation Techniques", a three-year program which started in July 1982.

References and illustrations at end of paper.

Results of the first three projects have been reported in M.I.T. Sea Grant Reports published in 1974, 1977, and 1981.[1-3] Detailed results of the fourth project, which is discussed in this paper, will be prepared in another M.I.T. Sea Grant Report currently under preparation.[4] To date, twenty students have prepared theses for B.S., M.S., Ocean Engineer, and PH.D. degrees covering various related subjects. This paper has been prepared based on the last two theses, by D.W. Schloerb[5] and H. L. Gustin[6].

The objective of the research covered in this paper is to develop fully automated and integrated systems which package many operations involved in welding, including feeding the electrode, manipulating the torch, etc., through careful engineering, so that the welding systems can be operated by a person with no welding skill. These systems have been nicknamed "instamatic® welding systems", since they are similar to instamatic® cameras with which a person with little knowledge of photography can take good pictures. The systems developed can be used for a variety of welding jobs for marine, nuclear, space, and other applications.

DEVELOPMENT OF "INSTAMATIC"® WELDING SYSTEMS

Arc welding processes, including shielded metal arc (SMA), submerged arc, gas tungsten-arc (GTA), and gas metal-arc (GMA) processes, are widely used for fabricating metal structures, including ships, bridges, pressure vessels, pipelines, etc. Most of welding operations are done manually by skilled welders. Even automatic welding machines are operated by workers specially trained for the job. In most welding jobs performed on land, it is assumed that qualified welders and trained operators are available. This assumption is usually valid when welding fabrication occurs in shipyards and other plants.

Likewise, underwater welding operations are almost exclusively done manually today. Underwater welding processes which are currently in use may be classified, depending upon the environment in which the welding operations take place, as follows[7]:

(1) Dry chamber processes in which welding takes place in a dry environment. They are further classified as (a) one-atmosphere welding, (b) hyperbaric dry habitat welding, or (c) hyperbaric dry minihabitat welding.

(2) Portable dry spot process in which only a small area is evacuated and welding takes place in the dry spot.

(3) Wet process in which welding is performed in water with no special device creating a dry spot for welding.

Again arc welding processes, including SMA, GTA, and GMA processes, are most widely used in all of the above groups.

The dry chamber processes are capable of producing high quality welds; however, they are very expensive primarily due to the high cost of deploying specially designed chambers and supporting facilities. The wet welding processes, especially the wet SMA process, are simpler and less expensive than dry processes; however, qualities of welds made by wet processes are rather poor and their uses are generally limited to repairs.

M.I.T researchers believe that it is quite possible to introduce automation in underwater welding for improving the weld quality and reduce fabrication cost.[7] Robots and other mechanical means can be used to assist the diver/welder for both dry and wet welding. This paper deals with the work on "instamatic"® welding, which is one way of introducing automation through (1) packaging of some of operations involved in welding fabrication and (2) standardizing joint configurations. Research efforts are currently underway on the use of remote manipulating techniques for underwater welding, and we hope to be able to report these results in the near future.

The concept of "instamatic"® welding was originally developed during an earlier study on joining and cutting techniques for deep-sea applications.[3] In order to successfully accomplish welding fabrication and repair, it is important to package some operations involved in welding so that very little welding skill is needed to perform the welding jobs. Development of such fully automated and integrated systems are desirable for the following reasons:

(1) In some underwater welding jobs, especially those performed in deep sea or in areas away from cities, it is difficult to secure a sufficient number of workers who are qualified in both diving and welding.

(2) In deep-sea operations, even a qualified diver/welder may not be able to perform high-quality welding jobs, because welding must be performed under severely adverse conditions.

Any mechanical devices which simplify the work that must be performed by the diver/welder should help to improve the quality of the work and reduce the construction cost.

M.I.T. researchers then realized that similar systems can be developed for a number of applications other than deep-sea welding. In fact, development of welding systems in dry environment is much simpler than those which must operate underwater, especially in deep sea. The research effort at M.I.T. toward "instamatic"® welding systems has led to the development of a novel concept of using an enclosed welding system. This system contains the piece to be welded in a "cassette", similar to a cassette tape installed in a tape recorder or a cartridge-type film installed in a new Polaroid camera. This idea is a radical departure from the current practice of welding fabrication. Currently, pieces to be welded are first assembled together, and a welder or a welding machine comes to the weld location to perform the welding. By contrast, the new concept is based on a cartridge welding device which contains a piece to be welded, and which automatically performs the desired welding by pushing just one button to activate the device.

One obvious restriction of this new approach is that such a system can perform only those jobs which have been predetermined for the system. However, we believe that by properly selecting joint geometries commonly used, a series of "instamatic"® welding systems can be developed which can perform a considerable percentage of the welding jobs needed in actual construction. Some of the relatively simple examples for using the instamatic® welding systems are as follows (see Figure 1):

(1) Stud welding of a bar to a plate, as shown in Figure 1a. Further discussions are given in a later part of this paper.

(2) Joining of a flat plate to a flat plate, as shown in Figure 1b. Further discussions are given in a later part of this paper.

(3) Lap welding of a cover plate to a flat plate, as shown in Figure 1c. Further discussions are given in a later part of this paper.

(4) Replacing a section of a pipe, as shown in Figure 1d.

Various other types of "instamatic"® welding systems can be conceived and developed.

It should be mentioned that the basic technologies and machine components needed for the construction of "instamatic"® welding systems are rapidly expanding today as follows:

(a) There is a surge of interest in the welding industry, in the increased automation and miniaturization of welding machines and tools utilizing modern electronics technologies. Some welding machines and power supplies using solid state devices are very small. Some of them can even be operated by an ordinary 110-volt electric outlet available at home.

(b) There has been a tremendous increase in the use of robots in welding and other manufacturing processes. Some components of these robots can be used as parts of "instamatic"® welding systems.

(c) Many newly developed machines and tools are very "smart" or "intelligent", since they are equipped with various types of advanced sensing and control devices. At present there is a strong interest in developing "smart" welding machines which have adaptive control capabilities. Until recently, all automatic welding machines have performed welding using predetermined welding conditions, with no adaptive control in process. However, M.I.T researchers under the direction of Professor Masubuchi have been working on a research program for developing "smart" welding machines for the girth welding of pipes.[8]

On the basis of the current technology of automatic welding machines, we believe that simple automatic welding machines with no adaptive controls are probably good enough for a number of "instamatic"® welding systems. However, more sophisticated machines which have adaptive control capabilities will be needed for other applications such as the welding of stationary pipes. In welding a stationary pipe, welding conditions change as welding progresses and the welding position changes. In order to successfully weld a pipe in all positions, a machine probably needs in-process sensing and control capabilities, or it must at least have a capability for changing welding conditions as the welding progresses in a pre-determined fashion. Some degrees of smartness may be needed in welding machines to be used in instamatic welding systems.

The "instamatic"® welding systems can be used for various applications as follows:

(1) Certain repair jobs which must be performed either on board a commercial or military ship or on an offshore oil drilling rig when no skilled welder is available. It is important to have the capability of performing some maintenance and repair jobs without a qualified welder.

(2) Rehabilitation of steel structures, especially off-shore oil-drilling rigs and other ocean engineering structures. Some of them need and will need various types and degrees of repairs. Unlike ships which can be brought to docks for repair, many repairs on off-shore structures must be performed in position, including underwater. Instamatic® welding systems may be used for some repair jobs, primarily minor repairs.

(3) Jobs requiring attachment of various metal pieces to ocean structures. For example, the attachment of anodes for corrosion protection is a major maintenance job on ocean structures. There are many other minor jobs for attaching metal pieces with various shapes and sizes to ocean structures, for a variety of purposes. Many of these welding jobs may be done by instamatic® welding systems.

(4) Certain welding jobs which must be performed in hazardous environments, such as in compartments where sparks from the welding arc may cause fires or explosions. Since welding operations in an instamatic welding system are performed in an enclosed box, the possibility of causing fires and explosions from welding sparks can be minimized. There are other cases in which it is difficult or impossible to perform welding using humans, such as welding in areas filled with toxic gases. Instamatic® welding systems, perhaps activated by remote control, may be used in these cases.

Also, instamatic® welding systems can be used for a variety of non-marine applications. For example, they may be used for various repair jobs of nuclear reactors. They may also be used for maintenance and repair of space stations. In fact, instamatic® welding systems may well be used for many applications through coupling with robots. By the proper use of instamatic® welding systems, simple and cheap robots can perform a variety of welding jobs for a number of applications.

The two-year research project performed at M.I.T. from July 1980 through June 1982 covered various tasks including (1) a background and market survey, (2) development of initial designs of various types of instamatic® welding systems, and (3) construction and testing of few selected systems. Two prototype systems have been constructed and tested. One is a diver-operated underwater arc stud welding system, while the second system employs gas metal arc welding. The remainder of this paper describes these two systems. Further details of the research are given in References 4, 5, and 6.

UNDERWATER STUD WELDING SYSTEMS

One of the first practical applications of stud welding was in the shipbuilding industry, where it was developed in the late 1930's as a means of attaching large numbers of fasteners to the steel plates of a ship[9]. Since then, stud welding in air has found wide applications wherever the attachment of a large number of studs is required. A variety of stud shapes, sizes, and materials have been successfully employed.

Conventional stud welding equipment consists of a stud gun, an electric controller, and a D.C. power source. To make a weld, the operator simply loads a stud into the gun, presses it against the work surface, and pulls the trigger. The electric controller then controls the sequence of the welding process according to predetermined settings.

Stud welding can be classified into two basic types, depending upon the type of power source used. The first type, capacitor discharge stud welding, employs a bank of charged capacitors as the power source. Because of the extremely short weld time associated with this technique, on the order of milliseconds, capacitor discharge stud welding is inherently limited to studs smaller than approximately 1/4 inch in diameter. On the other hand, the second type of stud welding, known as arc stud welding, can weld studs of more than one inch in diameter.

Because of the simplicity of this process and the ready availability of conventional land stud welding equipment, M.I.T. researchers have been interested in stud welding for use underwater since 1974. Similarly, a number of other groups around the world have studied underwater applications of stud welding.[10,11] Underwater stud welding was first studied at M.I.T. by Zanca[12], who developed a prototype capacitor discharge stud welding gun for underwater use. A U.S. patent on an underwater stud welding gun was granted to Masubuchi and Kutsuna.[13]

Underwater arc stud welding was first studied at M.I.T. by Chiba[14,15] in 1976. He welded studs in a shallow, one inch deep tray of water using an experimental set-up as shown in Figure 2. The 3/4 inch diameter studs were welded to 1/2 inch and 1 inch thick mild steel and HY-80 steel plates. HY-80 is a quenched and tempered steel with the specified minimum yield strength of 80,000 psi. Good quality welds were obtained in both air and underwater welding.

Chiba found that most stud welds made in air and underwater performed satisfactorily in both tensile and bend tests.[3] In most cases, fractures occurred at the threaded portion of the stud. Examinations of metallurgical structures and hardness were made on several specimens on a cross section, as shown in Figure 3. An interesting observation was that the maximum hardness obtained in the heat-affected zone in the base metal (location 4 in Figure 3) was little affected by the presence of water. This can be explained as follows: cooling rates of regions near the outer surface of the stud are affected by the presence of water; however, those in regions near the center of the stud are little affected by the presence of water.

Stud welding is fundamentally suited for underwater wet welding, compared to other welding processes such as shielded metal arc welding. In wet shielded metal arc welding, molten metal from the electrode must be transferred in small particles travelling in the arc atmosphere surrounded by water. As the arc moves, the weld metal is exposed to a large mass of water which has the tremendous quenching effect to the weld. On the other hand, in the case of stud welding, metals in the central portions of the stud are very little affected by the presence of water, if the small amount of water that existed between the stud and the base metal is squeezed out from the weld region when the stud is pushed against the base plate, toward the end of the welding operation.

Kataoka[16] continued the study of underwater arc stud welding. The stud welding gun and test specimens were placed in a pressure tank to simulate dry and wet welding in deep sea. Kataoka found that increased pressure caused the arc to bend and become unstable. He was able to produce "good quality" welds with 1/2 inch diameter studs in air and water up to a pressure of 50 psig.

Encouraged by the success achieved by Chiba and Kataoka, Schechter[17] began the development of a stud welding gun which could be completely immersed in water. In previous studies by Chiba and Kataoka, tests had been made with the work surface horizontal, because the gun used in the tests could not be allowed to get wet. Schechter determined that the gun should (and could) be designed to be "water-floodable" rather than waterproof. This idea, which was originally suggested by Mr. Charles Parker of the M.I.T. Stoboscopic Laboratory, is based on the fact that it is much easier to make the working mechanism of the gun so that it could be immersed in water, than it is to try to keep the water out. Schechter also designed a flexible ferrule mounting which made it possible to make good welds even when the stud welding gun is not held exactly perpendicular to the work surface. In underwater welding, it is rather difficult to position the welding gun exactly perpendicular to the work surface.

Schloerb[5] picked up where Schechter left off. In particular, Schloerb was to construct a fully submersible arc stud welding gun. His further goal was to develop a practical system which could be tested in the field. Schloerb, who has diving skill, decided that the welding system should be diver-operated. Naturally, a diver-operated system is not the only approach. Indeed, a remotely operated system would have a significant advantage in the deep sea. However, the development of a diver-operated system was felt to be of immediate practical benefit to the industry. Efforts are currently being made to further develop stud welding systems which could be remotely operated from an underwater vehicle.

A prototype of the underwater arc stud system was constructed, and a number of developmental tests were carried out. The final design which was developed is believed to be reasonably good, although further improvements are currently being made. Figure 4 is a schematic diagram of the final design by Schloerb.[5] Key features of the gun are shown.

The system incorporates a conventional diesel stud welding generator and a conventional electronic controller which are located out of the water. The trigger switch, which initiates the weld cycle, is also located on the surface for safety reasons. This switch is incorporated in a knife switch which assures that electrical power to the stud gun is only on when a weld is actually being made. The knife switch is operated by the diver's tender on command from the diver. An electrical umbilical connects the surface equipment to the submersible arc stud welding gun.

The heart of the stud gun is the stud lifting mechanism. This mechanism lifts the stud a predetermined distance in order to produce a precise arc gap between the end of the stud and the work surface. The arc gap is adjusted by moving the lift mechanism along the support framework.

The force to lift the stud is generated by a solenoid which is activated by the control unit. The control unit initiates the welding arc at the same time as the stud is lifted. The arc causes the end of the stud and a portion of the work surface to melt. After a predetermined time, the control unit stops the arc and de-energizes the solenoid. At this point, a spring forces the stud back against the work surface. A disposable ceramic collar, called a ferrule, is held in place around the base of the stud to prevent weld splatter. The molten metal solidifies quickly leaving the stud welded to the work surface.

The system employs conventional ferrules and a conventional ferrule clamp. The ferrules are press-fit on the ends of the studs, using steel wool prior to the dive in order to make it easier for the diver to handle them. The steel wool also serves as an arc initiator.

Considerable work has been done to make the entire system as simple as possible. As a result, the lifting mechanism has only one moving part--the lifting rod which transmits force to the stud. Another key feature is the fact that the lift mechanism is "water-floodable" rather than waterproof. A plastic case prevents electolysis of the lift mechanism components and helps to reduce the extent of the electric field which surrounds the gun.

A major part of the work done in developing the stud gun has been an investigation of the electric field in the water around the gun. Preliminary calculations anticipated that this field would present a hazard for the diver who is operating the gun. This was confirmed by measurements which found the magnitude of the electric field near the gun to be more than 100 times the recommended safe limit. A conventional underwater welding stinger, on the other hand, was found to produce a field whose magnitude was just equal to the safe limit.

It has been proposed that a grounded aluminum shield, placed around the stud, could be used to reduce the field to a safe level. Development of the shield is not complete. A preliminary shield design was found to reduce the magnitude of the electric field by a factor of 20.

In addition to the components described above, the stud gun consists of the following basic parts: a chuck holder, which adapts to conventional stud welding chucks, connects the lifting rod to the stud and serves as the "hot" electrical connection; and, a permanent magnetic base employed to hold the gun in place during the welding operation. The base will attach to both flat and cylindrical surfaces.

"INSTAMATIC"® ARC WELDING SYSTEMS

Initial work for the development of "instamatic"® systems using arc welding processes was performed during an earlier research project on joining and cutting techniques for deep-sea applications.[3] Lombardi[18] worked on the development of an enclosed unit for underwater welding using flux-shielded process. In fact, his study followed earlier studies by Tsai[19] and Erickson[20]. Tsai who was studying methods for preventing rapid quenching of underwater wet welds, thought that submerged arc welding might be a good process to be used underwater since the weld metal is covered by a flux. Masubuchi and Tsai[21] obtained a U.S. patent on underwater submerged arc welding. Erickson[20] then studied effects of pressure on flux-shielded arc welding underwater.

Figure 5 shows the conceptual design developed by Lombardi of an enclosed unit for underwater welding using the flux-shielded process. For deep-sea applications, the entire unit shown here probably needs to be installed in a strong, watertight vessel. The machine consists of a motorized carriage which simultaneously provides the consumable electrode feed into two torches, and the wire feed speed. These electrodes are connected via cables to the power supply which is not shown here. A plate to be welded is placed securely between the torches, parallel to the line of travel. Stainless steel foil moulded 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. Figures 6a through 6c show the sequence of the operation. First, the machine is placed upon a steel object on which the welding will take place, as shown in Figure 6a. The machine is then evacuated of all water, creating a local dry environment 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 arc, being of high temperature, will burn through the foil and can be maintained 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, as shown in Figure 6d. Lombardi constructed a prototype and found that the basic concept is sound, although his tests have only been done in air.

Gustin[6] continued the work started by Lombardi. However, Gustin's work differs from that of Lombardi in the following ways:

(1) Gustin's work is primarily directed toward developing a machine to be used in air, while Lombardi's work was aimed at developing a machine to be used underwater;
(2) Gustin decided to use gas metal-arc (GMA) process which is easy to control; and,
(3) Regarding the joint configuration, Gustin decided to work on lap welding a circular cover plate to a flat plate, as shown in Figure 1e. It was felt that Lombardi's work was enough to show that an insamatic welding system can be built for joining a plate to a plate by fillet welding, as shown in Figure 1c.

Gustin designed and constructed a device capable of welding a circular "cartridge" of low-carbon steel to a base plate of similar material Figure 7 shows the schematic of the design which can be summarized as follows:

(1) A GMAW (MIG) gun is mounted on a shaft so that rotation of the shaft causes the gun to transverse the desired circular path.

(2) A cartridge holder is mounted concentrically on the shaft. The cartridge holder accepts the patch to be welded and mechanically positions the patch against the base plate. A bearing component of the cartridge holder allows the shaft to rotate without requiring holder rotation.

(3) The enclosure shown provides structural support for the other components. In addition, the enclosure provides the potential for using the device as an isolated welding system.

Commercial welding devices (e.g., power supply, shielding gas, cooling water systems, wire feed equipment, etc.) are used in conjunction with the illustrated equipment to perform the desired circular patch weld.

The designed system was tested successfully in a laboratory environment. Good quality welds were obtained judging from their bead and heat effect uniformity, good fusion characteristics, absence of any burn-through, and adequate weld penetration.

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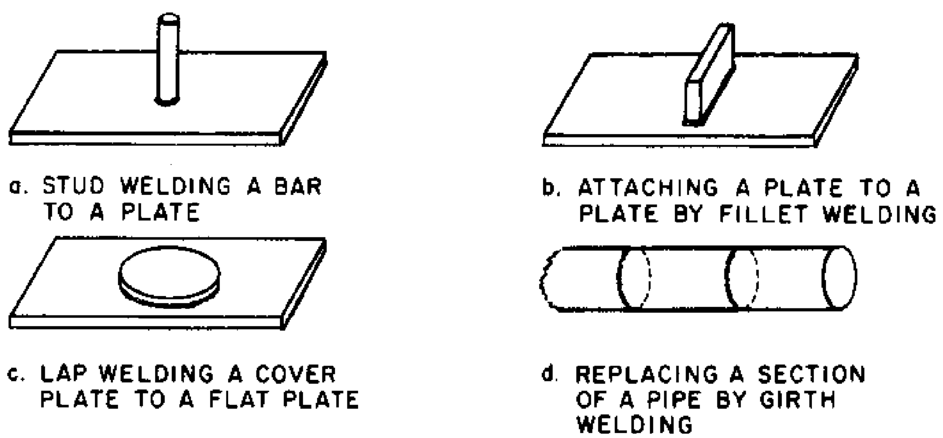


Fig. 1—Several basic joint types investigated for welding by "Instamatic"® systems.

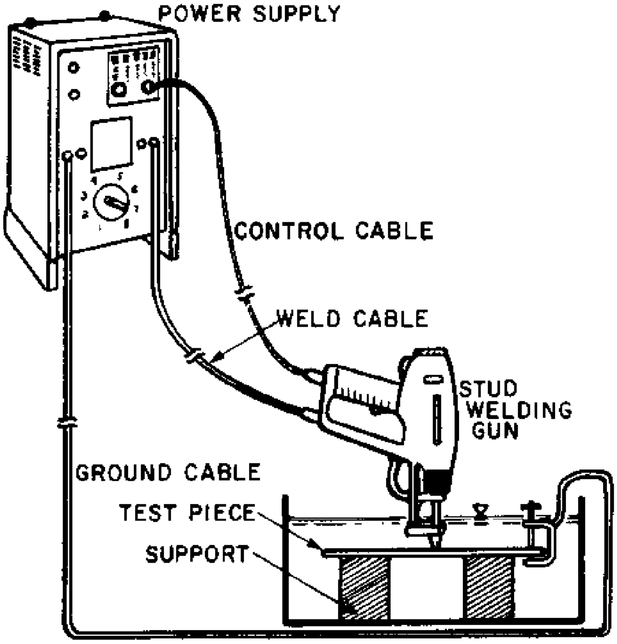


Fig. 2—Arc stud welding setup used by Chiba.

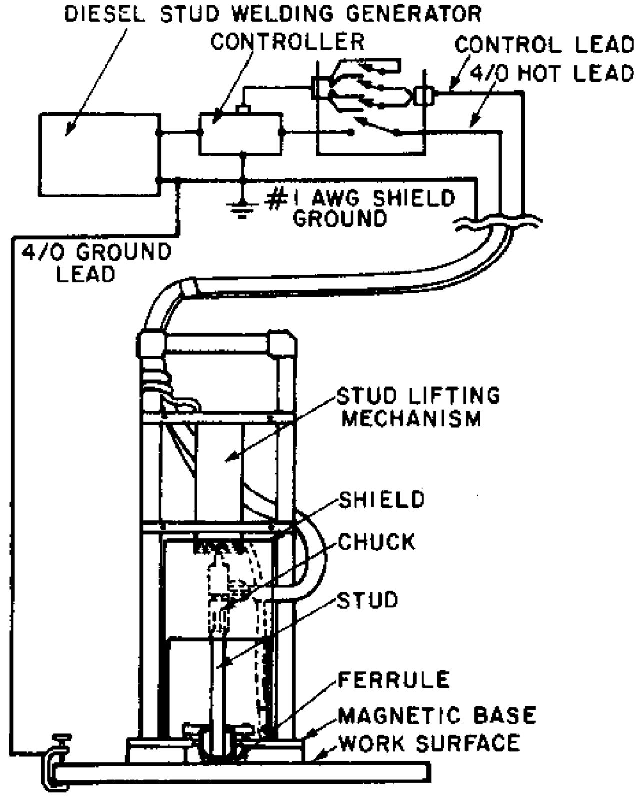
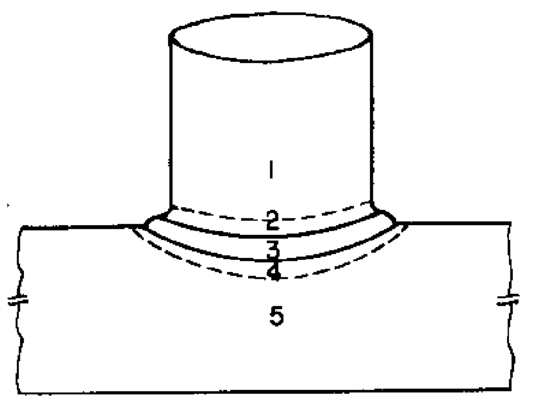


Fig. 4—Diver-operated underwater arc stud welding system developed by Schloerb.[5]



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

Fig. 3—Cross section of a stud welded joint.

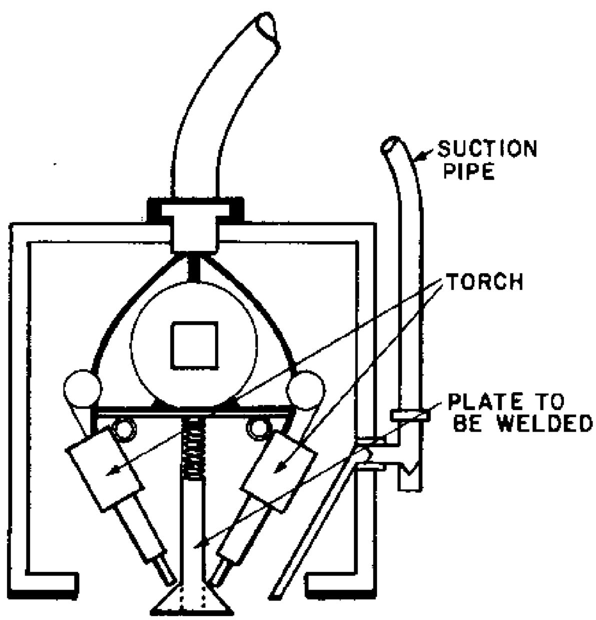


Fig. 5—Conceptual design of automatic underwater welding machine developed by Lombardi.[3,18]

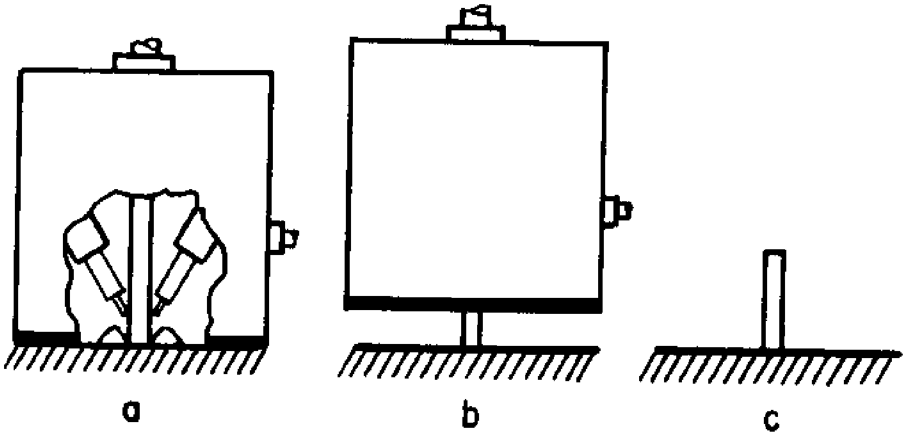


Fig. 6—Welding procedure sequence of automatic underwater welding machine.

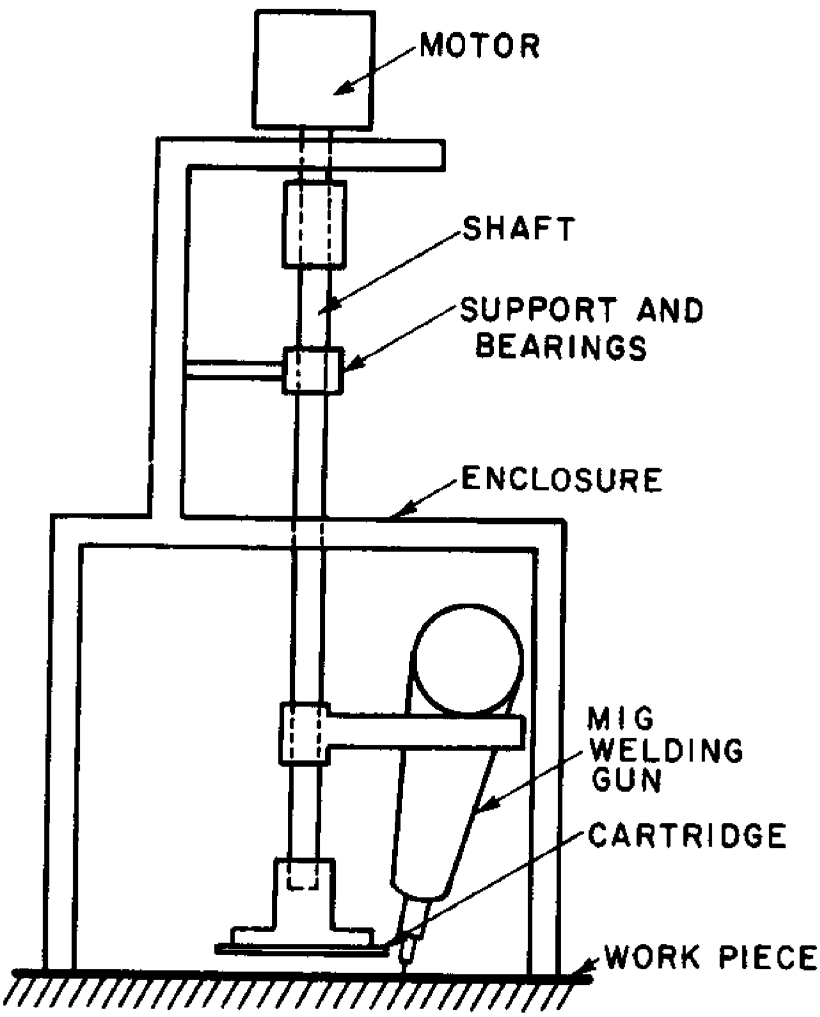


Fig. 7—Rotary cartridge welder.

APPENDIX B

BEHAVIOUR OF OFF-SHORE STRUCTURES

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AUTOMATION IN UNDERWATER WELDING

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SUMMARY

In recent years a rapid growth in the offshore industry with a concurrent increase in operational depths has been witnessed. As a consequence, underwater operations, including inspection, maintenance, repair and construction, will have to be performed at ever increasing depths. To successfully perform these operations automatic devices that will aid the skilled workers/divers in their jobs or, optimally, diver-alternative work wystems will have to be developed. This paper addresses the subject of automation in one of the aforementioned operations, namely underwater welding.

First a brief summary of the present state-of-the-art of underwater welding is given. Both dry and wet processes are discussed together with their applications and the major problems associated with them. This is followed by a description of recent research efforts at the Massachusetts Institute of Technology aimed at developing simple fully automated and integrated ("instamatic") welding systems for marine applications. Two of these systems, one for underwater stud welding, and the other based on the concept of cartridge-based packaging of welding, are described in some detail. Finally, future possibilities in more advanced underwater welding automation are described, including the use of supervisory controlled undersea teleoperators.

INTRODUCTION AND BACKGROUND

Offshore oil drilling and other ocean-related industries have grown tremendously in recent years and they are expected to grow in the future. As the number of ocean engineering structures has increased, there has been an increased demand for underwater construction, inspection, and repair of these structures.

An important characteristic of the recent developments is an increase in operational depths. Offshore production facilities are now operating to depths in excess of 1,000 feet; pipelines are being laid to depths of 2,000 feet; and exploratory drilling is reaching 5,000 feet and beyond. At the same time the U.S. Navy has shown an increased interest in deep water operations, as can be seen by the recent establishment of a National Research Council Committee to study and identify potential applications in this area. As a consequence underwater operations, including inspection, maintenance, and construction, will have to be performed at ever increasing depths.

To meet the 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. Despite these advances, however, the overwhelming majority of underwater welding operations are currently performed manually by skilled welders/divers.

Presently, divers can work competitively at depths up to 350 ft of seawater depending on the task (Eppig, 1981). Beyond these depths bottom time is limited largely due to the lengthy compression/decompression time required. Furthermore, factors having to do with depth per se (such as life support equipment) become increasingly costly, whereas at the same time personal safety is more and more difficult to maintain (as evidenced by the rather alarming mortality figures for commercial divers in the North Sea). Finally, as operational depths increase, divers need to be assisted by machines in order to perform welding jobs requiring certain levels of skill; this is due to, among other factors, the reduction of the diver's dexterity and ease of vision.

It thus becomes obvious that the need exists for alternatives to divers for the successful performance of underwater welding in the offshore environment. Optimally these diver-alternative welding systems should have the dexterity and decision-making capabilities of the skilled welder/diver if deep sea operations are to be carried out in a satisfactory manner. In other words, there is a need for underwater welding systems having fully adaptive automatic control capabilities. To arrive at such a system a lot more research has to be done. Nevertheless, the first steps towards the realization of it have already been started and are described in this paper.

After a brief summary of the present state-of-the-art of underwater welding technology is offered, two relatively simple underwater automatic welding systems that have recently been developed by researchers at the Massachusetts Institute of Technology (M.I.T.) are described. Finally, a discussion of future possibilities in the automation of underwater welding operations by fully utilizing the robotic and electronic technologies will be given.

PRESENT STATE-OF-THE ART OF UNDERWATER WELDING TECHNOLOGY

Underwater welding processes which are currently in use may be classified into five groups, as shown in Table 1, depending upon the environment in which the welding operation takes place. In all five groups the arc welding processes, including shielded metal arc (SMA), gas metal arc (GMA), and gas tungsten arc (GTA), are the predominant ones. Today actual underwater welding jobs are alsmot exclusively done manually using skilled diver/welders, as previously mentioned. M.I.T. researchers, however, believe that it is quite possible to introduce automation in the welding processes aimed at improving the weld quality and reducing the fabrication cost.

The dry chamber welding processes are generally capable of producing high quality welds; they are, however, very expensive due primarily to the high cost of deploying specially designed dry chambers and supporting facilities, including the life support equipment. It is believed that these costs can be significantly reduced if welding operations can be performed by using robots and other mechanical means.

Compared to the dry chamber processes, the wet welding processes, especially the wet manual SMA processes, are simpler, less expensive, and more versatile; weld quality, however, is rather poor so that their applications are limited mainly to repairs. Robots can again be used to assist the welder/diver in making better quality welds under less stressed working conditions.

Applications. Joining of important structural members, such as strength members of oil drilling rigs and underwater pipelines, is normally done using the dry processes. A recent paper discusses the state-of-the-art of the hyperbaric underwater welding process and applications of the process primarily performed by the Taylor Diving and Salvage Company (Delaune, 1979).

Although most underwater welding jobs are done in shallow waters, it is possible to conduct welding in deep waters too. A major limitation in performing wet manual SMA welding in deep waters comes from the diving systems. When conventional diving equipments are used, it is difficult to successfully perform welding operations beyond a depth of 200 ft. Using a saturation diving system, however, it is possible to perform wet SMA welding up to a depth of 1000 ft or, perhaps, even deeper. It has been reported that under simulated test conditions oxygen cutting and wet welding have been successfully performed at depths up to 1000 ft and welds have been made at depths in excess of 1200 ft (Delaune, 1979).

The dry chamber processes can also be used for deep sea applications. For example, the one-atmosphere welding can be performed at any depth as long as a necessary diving system is developed. The hyperbaric chamber processes can also be used in deep sea. Weld quality is believed to be generally good, because welds are made in the dry environment. The cost, however, becomes extremely high, as previously mentioned. Much of the information regarding actual applications of the dry chamber arc welding processes are unfortunately kept as a commercial secret. Two recently published examples of such applications are:

(1) Dry habitat welding in the open sea at a depth in excess of 1000 ft performed by the Taylor diving and Salvage Company (Delaune, 1979).

(2) A three-year experimental, deep-water welding study conducted in the North Sea near Stavanger, Norway in which welds were made in 300 m (1000 ft) water depths. This study, completed in 1978, aimed at demonstrating the feasibility of welding at great depths under atmospheric pressure (Anon, 1978).

Problems Associated With Underwater Welding. There are a number of technical and operational problems associated with underwater welding that have to be addressed and solved before any meaningful automation of the processes can be made. It is not possible to discuss these problems in detail in this paper because they are quite diversed depending not only upon the environment (dry versus wet, with or without additional external pressure) but also on the particular welding processes (SMA, GMA, etc.). In this section a short discussion of the problems encountered in the wet arc welding processes will be given.

The unique feature of wet welding is that the metals to be joined are completely immersed in water, a fact causing much more severe problems than in the case of dry processes. The major effects of water on arc welding are:

(1) Due to the quenching effect of water, a weldment cools rapidly, resulting in a hard and brittle weld.

(2) Bubbles are formed due to the intense heat of the welding arc, increasing the probability of a porous weld metal.

(3) Hydrogen in the bubbles and in the surrounding water may cause hydrogen-induced cracking.

The above effects can be enhanced by the increasing pressure as one goes deeper and by the salinity of the water. Unfortunately, only a limited number of documents have been published describing the above phenomena, with the majority of underwater welding related publications describing primarily practical and operational aspects of the processes.

Three M.I.T. Sea Grant reports (Brown, et al., 1974; Tsai, et al., 1977; Masubuchi, 1981a) and two recent papers (Masubuchi, 1980; Masubuchi, 1981b) present detailed discussions on various subjects related to the above phenomena, including: (1) formation of bubbles surrounding the welding arc; (2) underwater welding arc physics and metal transfer; (3) heat transfer in underwater welds; (4) effects of pressure on underwater welds; (5) polarity effects in underwater welding; (6) waterproofing of electrode coating; (7) microstructures and hardness of underwater welds; (8) crack sensitivity of underwater welds; and (9) porosity and other types of defects in underwater welds.

It is hoped that further research efforts will enable us to better understand the fundamentals of the underwater welding processes and hence to improve their performance and utilization through automation.

AUTOMATIC UNDERWATER WELDING SYSTEMS DEVELOPED AT M.I.T.

Systematic research on underwater welding has been conducted during the last 12 years in the Department of Ocean Engineering, M.I.T., resulting in the generation of much valuable information on the subject (Brown, et al., 1974; Tsai, et al., 1977; Masubuchi, 1981a). During the last few years this research effort has convinced M.I.T. investigators that fully automated and integrated ("instamatic") underwater welding systems which can be operated by people with no welding skill can be developed. Such a development would be desirable for two reasons. First, in some underwater welding jobs, especially those performed in deep sea, it becomes very difficult to secure workers who are qualified in both diving and welding. And second, in deep-sea operations even a qualified diver/welder may not be able to perform high-quality welding jobs, because welding must be performed under adverse conditions.

The latest research effort at M.I.T. towards the realization of these "instamatic" welding systems for marine applications has led to the development of an interesting concept, that of an enclosed welding unit containing a piece to be welded in a "cassette". This idea is a rather radical departure from the current practice, where the plates to be welded are first assembled together and then a welder or a welding machine comes to the weld location to execute welding. Compared to this, the new concept is based on a cartridge welding device which contains the piece to be welded and which automatically performs the desired weld in one operation (for details see below).

Some of the relatively simple examples that have been studied for application using the instamatic welding systems are as follows (see Figure 1):

(1) Stud welding of a bar to a flat plate, as shown in Figure 1a. The feasibility of instamatic stud welding systems has already been proven (Masubuchi, et al., 1978). Recently, a floodable stud welding system has been developed (Schloerb, 1982) that has a flexible magnetic base and which can also be used for welding a stud to a curved plate or a pipe (see Figure 1b). Details of this system are described in a later subsection.

(2) Joining of a flat plate to another flat plate or of a pipe to a flat plate by fillet welding, as shown in Figures 1c and 1d. It has already been demonstrated that this can be done using the flux shielded process (Masubuchi, 1981a). An attempt is currently being made to develop a special flux that will enable welding in all positions. The currently available process can be used in the downhand position only.

(3) Efforts have been successful in developing devices of integrated and automated systems for lap welding a cover plate to a flat plate (patch welding), as shown in Figure 1e (Gustin, 1982). Details of the system are given in a later subsection.

(4) Various ways for replacing a pipe section, as shown in Figure 1f, have been studied. The major difficulty in this case is that welding must be performed in all positions unless the pipe can be rotated during welding. Then, welding conditions must be changed as welding progresses and the welding position changes. In order to successfully weld a pipe in all positions a machine probably needs in-process sensing and control capabilities. An automatic welding machine which has such an advanced adaptive control system may be called a "smart" welding machine.

Potential Uses of Instamatic Welding Systems. Efforts have been made to identify potential uses of instamatic welding systems. Some of these uses are as follows:

(1) Certain repair jobs on board a ship and an offshore oil drilling rig which must be performed when no skilled welder is available. It is important to have the capability of performing some repair works without having a skilled welder.

(2) Rehabilitation of steel structures, especially offshore oil drilling rigs and other ocean engineering structures. Many ocean structures were built during the last 10 years, especially since the oil embargo by the OPEC nations. Some of them need various types and degrees of repairs. Unlike ships which can be brought to docks for repair, many repair jobs of ocean engineering structures must be performed under water. Instamatic welding systems may be used for some repair jobs, primarily minor repairs.

(3) There are a number of jobs requiring attachment of various pieces to ocean structures. For example, the attachment of anodes for corrosion protection is a major maintenance job for an ocean structure. There are many other minor jobs for attaching metal pieces with various shapes and sizes for a variety of purposes to ocean structures. Many of these welding jobs may be done by instamatic welding systems.

(4) Instamatic welding systems can be extremely useful for many welding jobs required in salvage operations. An integrated device may be developed to lift a sunken object. A system also may be developed to close an opening by welding so that air can be pumped into the sunken structure to obtain enough buoyancy.

(5) Certain welding jobs which must be performed in a compartment where sparks from the welding arc may cause fires or explosion. In fact, many fires and explosions in ships and on oil drilling rigs occurred during welding. Many of these fires and explosions can be prevented when welding is performed in an enclosed box.

(6) Certain welding jobs which must be performed in hazardous environment, such as leaking chemical products and radioactive materials. In some cases it is difficult or impossible to perform welding by human welders.

Underwater Stud Welding. Stud welding in the dry environment has been used for many applications. However, the use of stud welding underwater had not been studied seriously until M.I.T. researchers discovered that stud welding could be successfully used underwater (Masubuchi, et al., 1978).

Two basic reasons make underwater stud welding a very good candidate for automation, especially for deep-sea applications:

(1) A key factor in underwater welding is how to remove water from the weld zone. In stud welding the stud to be welded can have direct contact with the plate, thus only a small amount of water can exist near the surfaces to be joined. The effect of water pressure is considerably less in stud welding than in an ordinary arc welding in which metal particles are transferred through the arc plasma.

(2) Virtually no skill is required. The stud can be placed inside the welding gun so that the whole operation can be performed in one single step.

A recent research study at M.I.T. has resulted in the successful development of an automatic floodable arc stud welding gun (Schloerb, 1982). Figure 2 presents a schematic diagram of the system which illustrates the key features of the stud gun.

The system incorporates a conventional diesel stud welding generator and a conventional electronic controller which are located out of the water. The trigger switch, which initiates the weld cycle, is also located on the surface for safety reasons. This switch is incorporated in a knife switch which assures that electrical power to the stud gun is only on when a weld is actually being made. The knife switch is operated by the diver's tender on command from the diver. An electrical umbilical connects the surface equipment to the submersible arc stud welding gun.

The heart of the stud gun is the stud lifting mechanism. This mechanism lifts the stud a predetermined distance in order to produce a precise arc gap between the end of the stud and the work surface. The arc gap is adjusted by moving the lift mechanism along the support framework.

The force to lift the stud is generated by a solenoid which is activated by the control unit. The control unit initiates the welding arc at the same time as the stud is lifted. The arc causes the end of the stud and a portion of the work surface to melt. After a predetermined time, the control unit stops the arc and de-energizes the solenoid. At this point, a spring forces the stud back against the work surface. A disposable ceramic collar, called a ferrule, is held in place around the base of the stud to prevent weld spatter. The molten metal solidifies quickly leaving the stud welded to the work surface.

The system employs conventional ferrules and a conventional ferrule clamp. The ferrules are press-fit on the ends of the studs, using steel wool prior to the dive in order to make it easier for the diver to handle them. The steel wool also serves as an arc initiator.

Considerable work has been done to make the entire system as simple as possible. As a result, the lifting mechanism has only one moving part--the lifting rod which transmits force to the stud. Another key feature is the fact that the lift mechanism is "water-floodable" rather than waterproof. A plastic case prevents electrolysis of the lift mechanism components and helps to reduce the extent of the electric field which surrounds the gun.

A major part of the work done in developing the stud gun has been an investigation of the electric field in the water around the gun. Preliminary calculations anticipated that this field would present a hazard for the diver who is operating the gun. This was confirmed by measurements which found the magnitude of the electric field near the gun to be more than 100 times the recommended safe limit. A conventional underwater welding stinger, on the other hand, was found to produce a field whose magnitude was just equal to the safe limit.

It has been proposed that a grounded aluminum shield, placed around the stud, could be used to reduce the field to a safe level. Development of the shield is not complete. A preliminary shield design was found to reduce the magnitude of the electric field by a factor of 20.

In addition to the components described above, the stud gun consists of the following basic parts: a chuck holder, which adapts to conventional stud welding chucks, connects the lifting rod to the stud and serves as the "hot" electrical connection; and, a permanent magnetic base employed to hold the gun in place during the welding operation. The base will attach to both flat and cylindrical surfaces.

The developed system has been successfully tested underwater at pressures up to 300 psi.

Cartridge-Based Packaging of Welding Systems. A "packaged" welding system is one in which the various subtasks involved in the welding operation (e.g., joint positioning, arc direction, weld travel speed) are predetermined by the hardware design of the welding equipment. In other words, the welded joint that can be produced by a particular packaged system is defined by the specific geometrical configuration of that system. For devices of this type, the operator is only required to place the equipment on the worksite and then operate on/off switches.

Packaged welding systems, although necessarily of a limited applicability range, appear to be a desirable alternative to current welding practices in certain occasions. In particular, in cases where the geometry of the weld is regular and can thus be prespecified, such equipment could be used very efficiently. This is especially true when ordinary manual welding has to be performed in dangerous environments, as for example in nuclear reactors where high radiation levels are present. Several examples of welding geometries for which packaged systems are envisioned are shown in Figure 1 and were discussed in a previous subsection.

Automatic packaged cartridge welding devices have three salient characteristics in addition to the packaging of the weld process:

(1) Because of the limitations designed into the devices, they are low in cost. Based upon literature received from manufacturers of welding robots and general automatic welding equipment, it is estimated that packaged equipment could cost as little as 10% of the cost of more sophisticated equipment capable of making the same welds.

(2) A particular type of weld can be reliably performed. This is true whether the machine is used repeatedly in the same situation (such as would be the case in a mass production environment), or occasionally, in diverse situations (for instance, emergency repairs).

(3) Devices considered herein require minimal operator skill. Ideally, the operator need only (a) insert the cartridge, (b) position the welder, and, (c) turn power on and off.

To explore the feasibility of such systems, a representative one was designed, constructed, and tested (Gustin, 1982). Figure 3 shows the schematic diagram of the developed device which is capable of welding a circular "cartridge" of mild carbon steel to a base plate of similar material (circular patch weld).

With reference to Figure 3, the elements of the design can be summarized as follows:

(1) A GMAW (MIG) gun is mounted on a shaft so that rotation of the shaft causes the gun to traverse the desired circular path.

(2) A cartridge holder is mounted concentrically on the shaft. The cartridge holder accepts the patch to be welded and mechanically positions the patch against the base plate. A bearing component of the cartridge holder allows the shaft to rotate without requiring holder rotation.

(3) The enclosure shown provides structural support for the other components. In addition, the enclosure provides the potential for using the device as an isolated welding system.

Commercial welding equipment (e.g., power supply, shielding gas, cooling water systems, wire feed equipment, etc.) is used in conjunction with the illustrated equipment to perform the desired circular patch weld.

The designed system was tested successfully in a laboratory environment. Good quality welds were obtained judging from their bead and heat effect uniformity, good fusion characteristics, absence of any burn-through, and adequate weld penetration.

In general we believe that one of the applications where packaged systems may possibly be especially effective is their use in conjunction with robots. The combination of instamatic and robotic capabilities offers a functional flexibility which neither one has by itself.

FUTURE POSSIBILITIES IN UNDERWATER WELDING AUTOMATION

In the previous section the development of simple fully automated and integrated ("instamatic") welding systems for marine applications was described. These systems are believed to be only the first step towards more sophisticated automatic underwater welding systems. The recent advances in microcomputer and microprocessor technologies have convinced M.I.T. investigators that as a next step systems capable of performing simple underwater welding operations by remote manipulation techniques should be and can be developed (Masubuchi and Papazoglou, 1981).

Initials efforts towards this goal are currently under way. They involve the integration of the instamatic underwater welding technology with the technology of underwater telemanipulators under supervisory control developed at the M.I.T. Man-Machine Systems Laboratory (Sheridan and Verplank, 1978; Yoerger and Sheridan, 1981). Teleoperators are defined to be general purpose submersible work vehicles controlled remotely by human operators and with video and/or other sensors, power and propulsive actuators for mobility, with mechanical hands and arms for manipulation and possibly a computer for a limited degree of control autonomy. Based on this definition, then, a manned submersible is not a teleoperator vehicle, but the attached manipulators are certainly teleoperators, requiring control through a viewing port or through closed-circuit video. Supervisory control is a hierarchical control scheme whereby a system (which could be a teleoperator, but could also be an aircraft, power plant, etc.) having sensors, actuators and a computer, and capable of autonomous decision-making and control over short periods and in restricted conditions, is remotely monitored and intermittently operated directly or reprogrammed by a person (Sheridan and Verplank, 1978).

The distinction between direct human control of a teleoperator and supervisory control of a teleoperator is made graphically in Figure 4. Under direct control the operator's control signals are sent directly to the remote manipulator, and sensor information is fed directly back to the operator. The "hand control" can be a master-slave positioning replica or a control joystick. Under supervisory control the operator's control signals are relayed through a local computer to the remote computer, which then processes the signals and acts on the information. The relayed signals are not necessarily the raw signals generated by the operator. In fact, the signal is usually a coded instruction of high information density which must be interpreted to be utilized. The operator's input could range from a purely manual analogic command to a highly abstract symbolic command. The remote computer not only interprets the local computer's messages but also acts on the sensor information available to it about its environment. The remote computer only relays information to the operator which is deemed important and necessary for effective supervision--the responsibility for the specific details of control is usually left to the subordinate computer.

Generally speaking, the supervisor control system enables the human operator to:

(1) plan the actions of the remote system in a way which greatly reduces the need for continuous manual control,

(2) monitor the system as it carried out the planned actions,

(3) intervene if problems arise with which the remote system cannot deal.

It is expected that the initial efforts of this research will focus on relatively simple welding tasks, primarily using dry underwater welding processes. The reason for such a direction is that any sophisticated welding automation scheme or the utilization of wet processes will make the interfacing and integration of the two aforementioned technologies much more difficult. At later stages, and after the initial efforts prove to be successful, one can put emphasis on upgrading the automation of the welding operation itself, possibly by using in-process sensing and control.

Anticipated Benefits. We believe that the offshore industry and other ocean related industries will receive direct benefits from the automation of underwater welding operations. The most far-reaching benefit will involve the enhancement of the capabilities of underwater work systems. Currently there exist several manned undersea work vehicles equipped with manipulators. The capabilities of these systems, however, are rather limited and involve relatively simple tasks. Their potential will be realized even further if they can also be fitted by devices capable of performing underwater welding.

Furthermore, given the fact that underwater operations are being performed at ever increasing depths and that as depths increase the economics of the currently available systems make them prohibitively expensive, it becomes evident that untethered, unmanned underwater work systems have to be developed. Although such systems do not exist at the present time, we believe that the developmental efforts currently underway in various parts of the world will soon make such systems possible. At that time we believe that we should be ready to equip them with several operational capabilities. Automatic underwater welding devices must be one of them.

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Table 1 Classification of underwater welding processes currently in use

A. Dry Chamber Processes. Welding takes place in a dry environment. 1. One-Atmosphere 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.

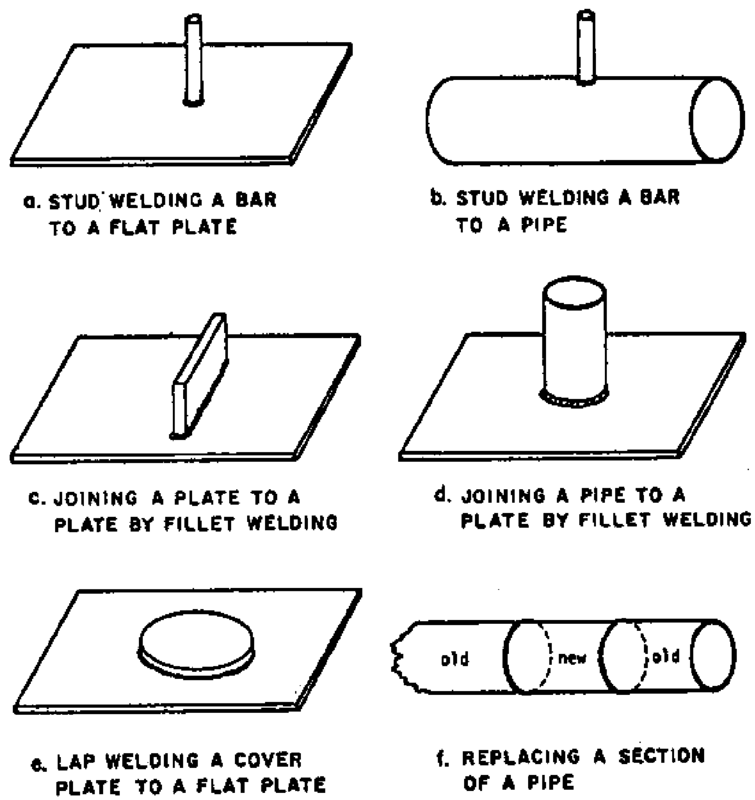

Figure 1 Several basic types of joints investigated for welding by instamatic systems

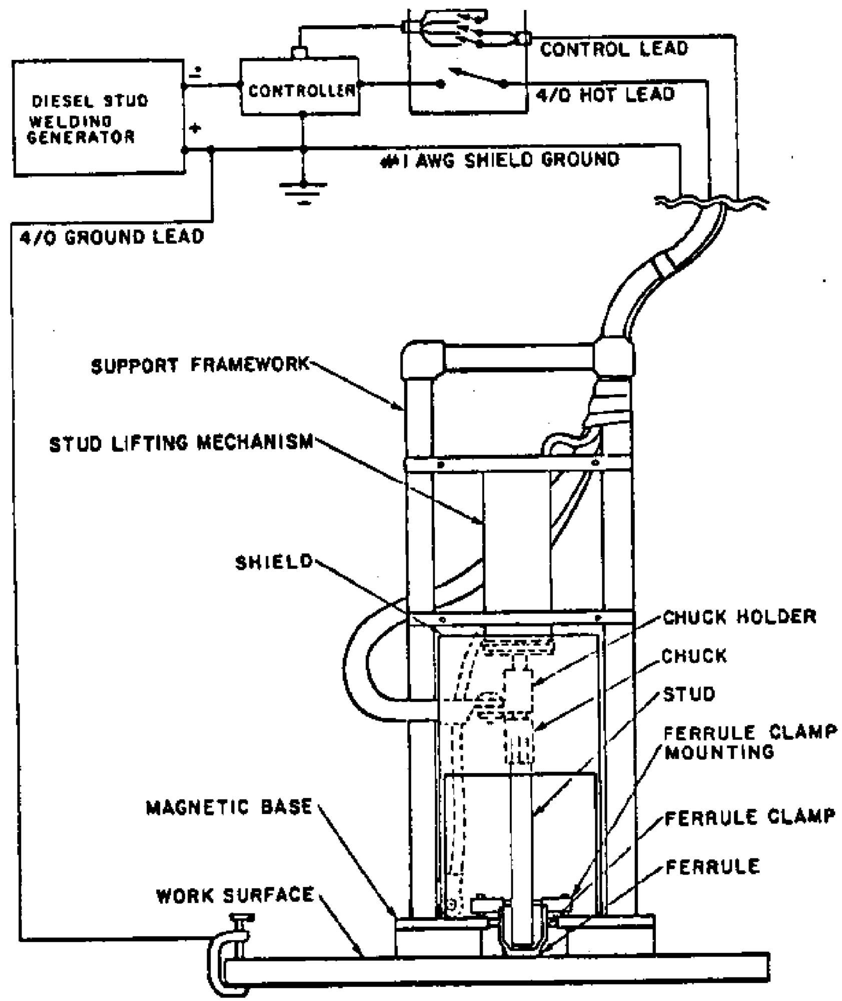

Figure 2 Diver operated underwater arc stud welding system

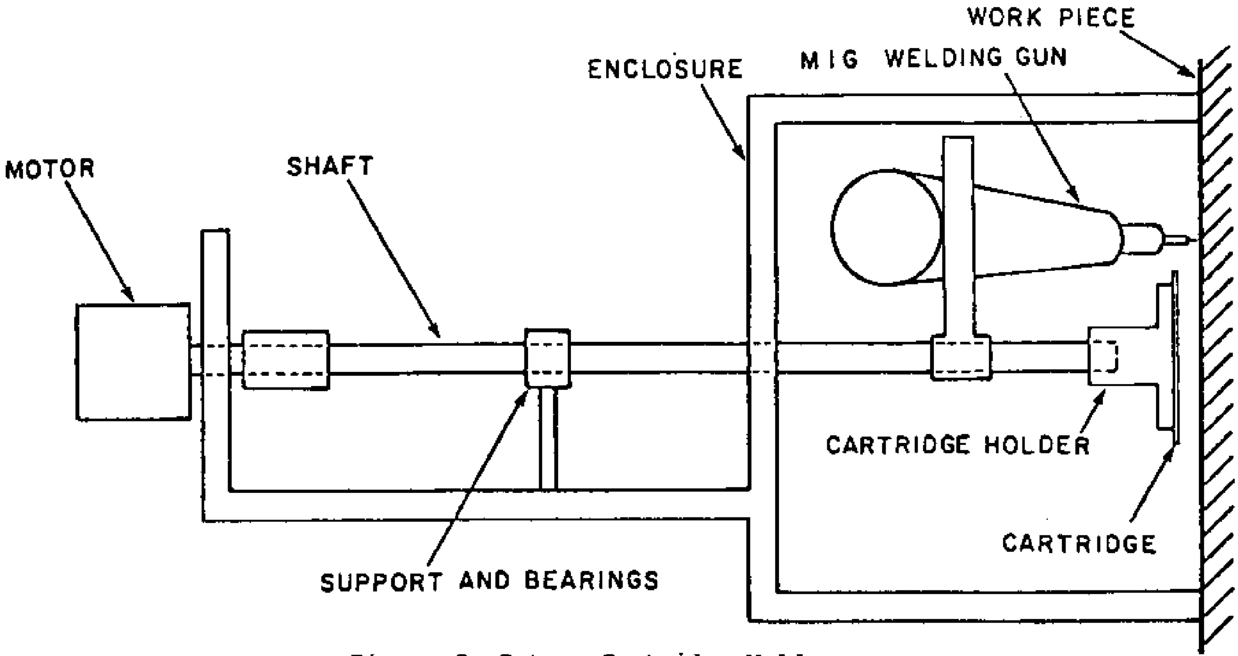

Figure 3 Rotary Cartridge Welder

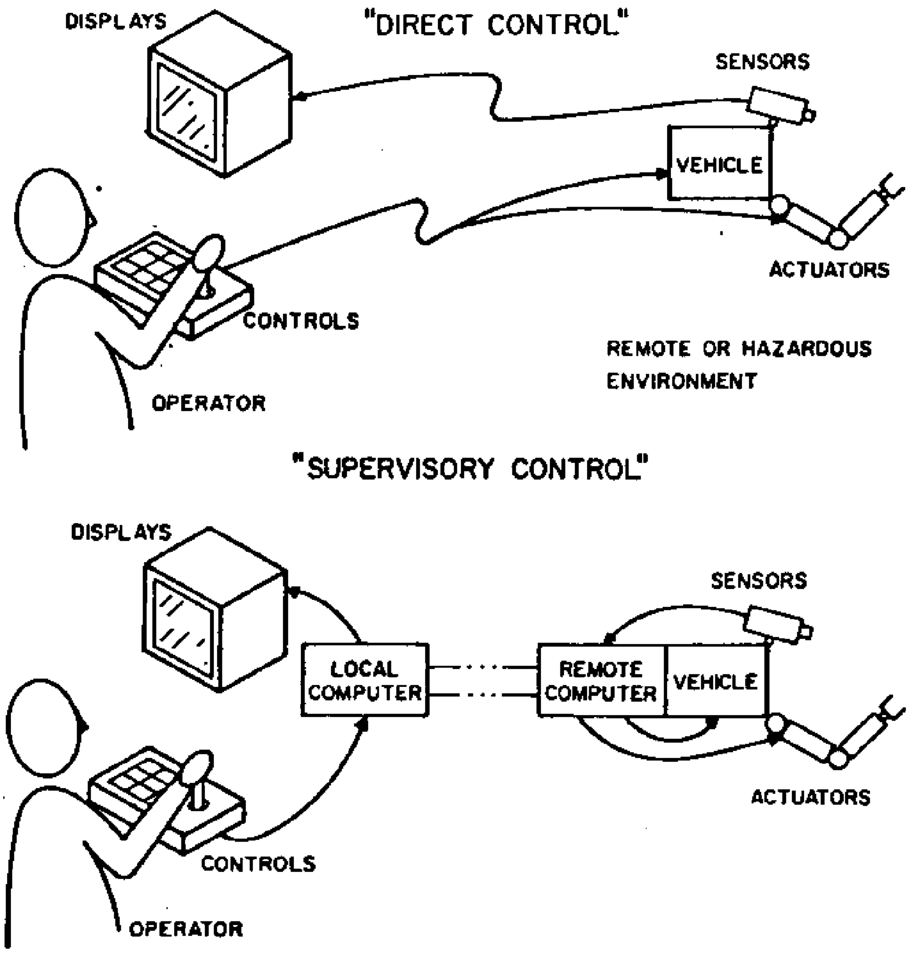

Figure 4 Direct manual control and supervisory control of a teleoperator