ROBOTIC VARIABLE POLARITY PLASMA ARC (VPPA) WELDING

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ABSTRACT

The need for automated plasma welding was identified in the early stages of the Space Station Freedom Program (SSFP) because it requires approximately 1.3 miles of welding for assembly. As a result of the Variable Polarity Plasma Arc Welding (VPPAW) process's ability to make virtually defect-free welds in aluminum, it was chosen to fulfill the welding needs. Space Station Freedom will be constructed of 2219 aluminum utilizing the computer controlled VPPAW process. The "Node Radial Docking Port," with it's saddle shaped weld path, has a constantly changing surface angle over 360° of the 282 inch weld. The automated robotic VPPAW process requires eight-axes of motion (six-axes of robot and two-axes of positioner movement). The robot control system is programmed to maintain Torch Center Point (TCP) orientation perpendicular to the part while the part positioner is tilted and rotated to maintain the vertical up orientation as required by the VPPAW process. The combined speed of the robot and the positioner are integrated to maintain a constant speed between the part and the torch. A laser-based vision sensor system has also been integrated to track the seam and map the surface of the profile during welding.

INTRODUCTION

The Space Station Freedom Program (SSFP) is an American-led international project. National Aeronautics and Space Administration (NASA), with subcontractors, will develop, launch and operate a permanently-crewed base in space by the mid-1990's. The space station will consist of an external structure, larger than a football field, connected to pressurized modules in which men and women will live and work in space. Boeing's role is to build the habitation and laboratory modules.

In order to manufacture the SSFP modules, new processes have to be developed. Innovative approaches have to be taken which will provide certifiable processes with the highest quality of workmanship in every step of the production of Space Station Freedom.

After careful review of all the process requirements, design configuration of parts and with flexibility in mind, the decision was made to acquire a welding system which will allow maximum flexibility and programmability. The welding system is to accommodate changes in configuration as the weldment designs are refined, also the workcell can be easily adapted to weld assemblies other than the Node Radial Docking Port (Figure 1).

SYSTEM SPECIFICATION

A specification was written to establish the basic requirement of the system, which will not only fulfill the process requirements, but also allow room for future expansion. In order to determine the robot's arm reach, motion simulation software was used.

Utilizing Deneb Robotics, Inc.'s graphic simulation package IGRIP (TM), the VPPA weld process profile motion was simulated. The simulation provided the preliminary location of the robot and weld fixture, which led to determination of the robot's arm reach. After performing several simulations, it was determined that a system with a minimum of 100 in/250 cm reach would be needed to perform the complex weld task. The simulation work was done in conjunction with NASA's Metal Processes Branch of Marshall Space Flight Center (MSFC) Productivity Enhancement Center.

Specifications were sent to nine different vendors. A vendor briefing was held at Boeing to answer all the questions regarding the specification. Five vendors participated in the question and answer session. Later, three vendors responded with proposals.

PROCESS

B. P. VanCleave, of The Boeing Company, along with Hobart Brothers of Troy, Ohio, combined the Plasma Arc process with Variable Polarity features in the late 1960's. As a result of VanCleave's promising work, a VPPAW research and development project was initiated in the late 1970's at NASA's Marshall Space Flight Center (MSFC) located in Huntsville Alabama, to determine the potential usage of the VPPAW process in the fabrication of space programs. Based on the success of the VPPAW process on the Space Shuttle's External Tank, Boeing selected the process as a key part of manufacturing the Space Station Freedom's Module and Node structures. The uniqueness of the VPPAW process is in the controlled manipulation of weld current pulse width and the addition of a controlled pulse of reverse polarity that supplies the cleaning action. The high velocity Argon gas flowing through the center of the orifice is an essential element to the process. The high velocity of the plasma arc punches a hole through the work piece known as a "Keyhole". The creation of the "Keyhole" in the workpiece opens up ahead of the plasma jet in the upward direction (direction of travel), and an impurity free molten puddle of aluminum flows downward, and solidifies behind the plasma jet. Because of this "blow-thru" mode of welding, the torch must maintain a "vertical-up" position during the entire welding process. Maintaining this orientation for joining straight or cylindrical plates is relatively simple and has been achieved using simple tools such as a two-axis manipulator and stationary fixture. Maintaining the "vertical-up" orientation becomes a complicated task when the weld seam geometry is in a three-dimensional orientation.

THE SYSTEM

The automated robotic VPPAW system, designed and integrated per Boeing's specifications by Cincinnati Milacron (currently ABB Robotics, Inc.) of Greenwood, South Carolina. The schematic diagram of the VPPA welding system is shown in Figure 2.

System Description

The cell is comprised of a Cincinnati Milacron T3(R)-696 Robot with control system, a Hobart HAWCS(R) VPPA Welding system, two Aronson RAB-60(R) positioners, a Stenning Weld viewing system, a perimeter guarding system , a gas manifold and monitoring system, and an operator console. The perimeter guarding system divides the workcell into three zones. In zones A and C, positioners are located, while zone B is the robot HOME zone (Figure 3). The two positioners were opted for the system to increase the efficiency of the workcell. While one assembly is being welded in one zone, a second assembly can be prepared for welding in a second zone.

Control

Cincinnati Milacron Acramatic(R) Version 5i robot control utilizes distributed microprocessor architecture and an MS-DOS(R) base operating system. It consists of a large option of hardware/software capabilities designed to facilitate efficient interfacing and controlling of external equipment and processes. In this workcell, the controller is interfaced with the safety monitoring system and weld control system. The robot control system acts as the master controller. A teach pendant is used to teach the robot and for programming the controls. The pendant could also be used for making correction of taught points for part deviations from the engineering design. Off-line programming capability also exists.

Robot

The robot is a standard six-axes articulated all electric servo-controlled unit consisting of dual resolver feedback for absolute positioning capability. The robot has a 275 lbs. load capacity at the end of the arm. End of the arm tooling consists of a welding torch with cross slide, AVC, torch rotator, wire guide manipulator and viewing camera (Figure 4). The position accuracy is within 0.010 inch.

HAWCS(R) VPPA Welding System

The HAWCS(R) system consists of an 80386 AT(R) industrial computer. The HAWCS(R) is the heart of the welding system. All the welding parameters and process controls are programmable. The typical welding program sequence is shown in Figure 5. It is the sequence of instructions that is executed by the controller to control the entire weld procedure as programmed. The automated voltage control (AVC) provides feedback to the control system, through utilization of computer software, and arc voltage is adjusted by changing the torch-to-work piece distance accordingly. All the procedure editing and execution, as well as system configuration and administration, are accessible through a VGA monitor which has a touchscreen interface for data entry. Each weld procedure is comprised of four segments: Start Up, Main, Termination and Emergency. The teach pendant provides remote display of weld parameters as well as trim capability, gas purge control and weld start/stop control. The HAWCS(R) control communicates with the robot control via its digital input/output (I/O) control to Robot I/O control. Position and velocity data is communicated to the HAWCS(R) control by a programmable digital to analog convertor which emulates a single channel encoder by sending a five volt DC digital pulse every 0.010 inches of torch center point motion. The welding parameters can be printed as well as stored on the disk during the weld in real time.

Operator Console

The operator console contains the operator interface for selecting programmed weld sequences, perimeter guarding, system status and intervention. Also included at the console are the weld viewing system, pendant for the control of the robot and for the HAWCS(R), and the monitors for seam tracking and bead profiler system.

Positioner

The RAB-60(R) is a two-axis positioner with servo-motor which is controlled by the robot control. The positioner provides tilt and rotation axes for part positioning. The positioner can carry a payload of up to 6,000 pounds. The positioners can rotate +/-458° and tilt 0 to 110°. The positioner axes may be moved using the robot pendant in either Manual Mode or in Teach mode. The positioner axes can also be programmed for part set-up in one zone while the robot is operating in Auto Mode in another zone.

Weld viewing system

In order to provide a safe robotic weld workcell and also to detect the shape of the groove and view the torch and wire tip manipulator, a remote viewing method has been utilized. A viewing system with filtration, which provides a uniform image of the welding arc, the weld pool, and the adjacent area was selected. The remote controlled viewing system provides substantially more real-time information to the welding operator and aids in making the needed adjustment while the weld is in progress.

The Stenning viewing system is comprised of a camera and light source located at the torch and a monitoring and control unit at the operator console. The viewing system has remote controlled focus, filter and iris, it also has the capability to video tape the weld utilizing a VCR.

Gas control

The gas manifold system is for dispensing and metering shielding and plasma gas. Manifold pressure is monitored by a pressure switch which is interfaced with safety control system which runs as a shell to the entire system. When pressure drops below 600 psi the LOW PRESSURE light is illuminated on the operator console.

SEAM TRACKING AND BEAD PROFILING

Seam tracking and bead profiling sensors have been added to the robotic end effector. It is intended to provide fully automated VPPAW welding with override capability of the remote control functions of cross slide and torch rotation control at the operator console. A square butt weld joint configuration with a slight edge chamfer will be utilized for the first pass seam tracking. The chamfer will not be visible for second pass welds, which also must be tracked. The system will be used to track the seam during root pass welding, as well as cover pass welding. For second pass tracking, the system will use the encoder tracking information from the first pass combined with a template matching algorithm based on the data from the first pass. The system mounting is shown in Figure 6.

Seam Tracking

A non-contact sensor will align the torch with the seam to be joined. It will position and track the center line of both the root and cover passes. The sensor is mounted on a position relative to the torch so the seam area is just ahead of the torch center point. The sensor moves forward along the seam in tandem with the weld torch, scanning the seam area from the torch side of the weld joint, and mapping the surface profile so the complete and true geometry of the seam is known and the torch is able to anticipate it and adapt accordingly. The sensor has been mounted in such a way that the seam is always in the field of view.

Bead Profiling

A non-contact laser vision sensor mounted behind the torch will be used to measure all of the weld parameters as shown in Figure 7 (at end of report). The prime purpose of the bead profiler is to measure and control the solidified weld bead parameters during the VPPA weld processes. The system will operate during VPPA welding and will be used to correct asymmetric bead profile. The sensor has been mounted one inch below the torch and measures the weld bead as soon as possible after solidification. The bead profiler will also control rotation of the torch to correct the bead's geometry by eliminating asymmetrical undercut contour. As the bead profile sensor senses the bead undercut, or any other asymmetrical contour of the bead, the torch would be rotated to correct this.

The data collected from seam tracking and the bead profiler's geometry parameter acquisition will be used for real time adaptive control and/or statistical process control (SPC) analysis.

Safety

The Perimeter Guarding System is comprised of six photo cell beam stands located in the front and rear of the cell. Each beam stand is comprised of three photo cells (sender / receiver). The photo cell beams guard against inadvertent entry into the cell or an unauthorized area of the cell. There are two gates located in zone "A" and "C" Figure 3. The gates are interlocked to the perimeter guarding system by use of a unique configured key system. The operator must have permission to enter that area of the cell before the key can be removed from its holder in the operator console. The operator can override the guarding system, under certain given conditions, allowing access to the non-working zone of the robot. Any unauthorized entry into the working zone of the cell results in an Emergency Stop being generated.

SYSTEM OPERATION

In order to run the system, weld parameters and robot motion have to be programmed. Several standard sub routines have been developed in the system for weld parameters and robot motion, thus minimizing the programming efforts required for different parts.

The automated welding system was installed in January, 1991. After initial training, the system became operational in February, 1991. The weld schedules for different thickness plates were developed and tested utilizing vertical test stands. Off-line simulation was used to determine the optimum location of the positioner in zone "A" and "B" Figure 3, to place the saddle shaped node radial docking port, window panel and cupola within the robot's reach. The node radial docking port was the first part to be welded on this system.

Part programming

The VPPAW process requires that the torch remain basically perpendicular with a 3° lead angle with respect to the part to maintain optimum molten metal orientation. The robot must be programmed to maintain Torch Center Point (TCP) orientation perpendicular to the part while the part is tilted and rotated to maintain the vertical-up orientation. The combined speed of the part and the torch must remain constant during the weld, with the exception of the start and termination points. The start-up requires ramp-up acceleration, while the termination requires tapered deceleration.

The node radial docking port weld path is saddle shaped, and thus has a constantly changing surface angle over 360°. The weld fixture and node radial docking port must be placed on the positioner with a clamp ring bolted to the fixture. The clamp ring is very carefully placed to assure that no gap exists between the part and the fixture. The clamp ring must be tightened down following a star pattern tightening sequence to ensure that there is minimum distortion of the part. The clamp ring also provides a heat sink function.

The first programmed point was generated by tilting and rotating the positioner and moving the robot to the weld starting point so that the torch and part surface became perpendicular to each other. Subsequent points were generated by tilting and rotating the positioner about 3° while moving the robot vertical up so that the part remained perpendicular to the torch. Approximately 130 points were generated along the saddle path. In order to program the saddle path accurately, devices such as a trisquare, inclinometer and a spring loaded torch head were utilized. At each point, the trisquare was used to ensure that the part was vertical with respect to the earth and the torch was perpendicular to the part on the horizontal axis. The inclinometer was used to ensure that the torch orientation was such that the tip of the torch was 3° above the horizontal plane. The spring loaded torch head was used to make sure that the torch tip would be on the center of the seam. Each point was measured and checked carefully prior to programming.

The total weld path motion was 282 inches, requiring 200 + points and eight-axes of coordinated motion were programmed to accomplish the saddle weld. Three different welds were made on the part, tack at eight inches per minute (IPM), root pass at seven IPM and cover at ten IPM. The welds were right on the seam during the entire weld procedure. The robot tracked the seam very accurately with minimal (+/- 0.010") deviation from the weld path. One concern was that .here would be part deflection due to heat from the weld which would effect the path; however, there was very minor deflection of the part, due to the heat sink of the clamping ring and fixturing.

CONCLUSION

The production workcell has been installed and successful VPPA welding has been accomplished on development articles. The cell is currently operational for the production of Space Station Freedom.

The use of the eight-axes controlled motion is the first known production application of a robot in tandem with the Variable Polarity Plasma Arc Welding System. Implementation of this system will allow expansion of the high quality VPPA weld process to part configurations that have not been considered good candidates.

ACKNOWLEDGEMENTS

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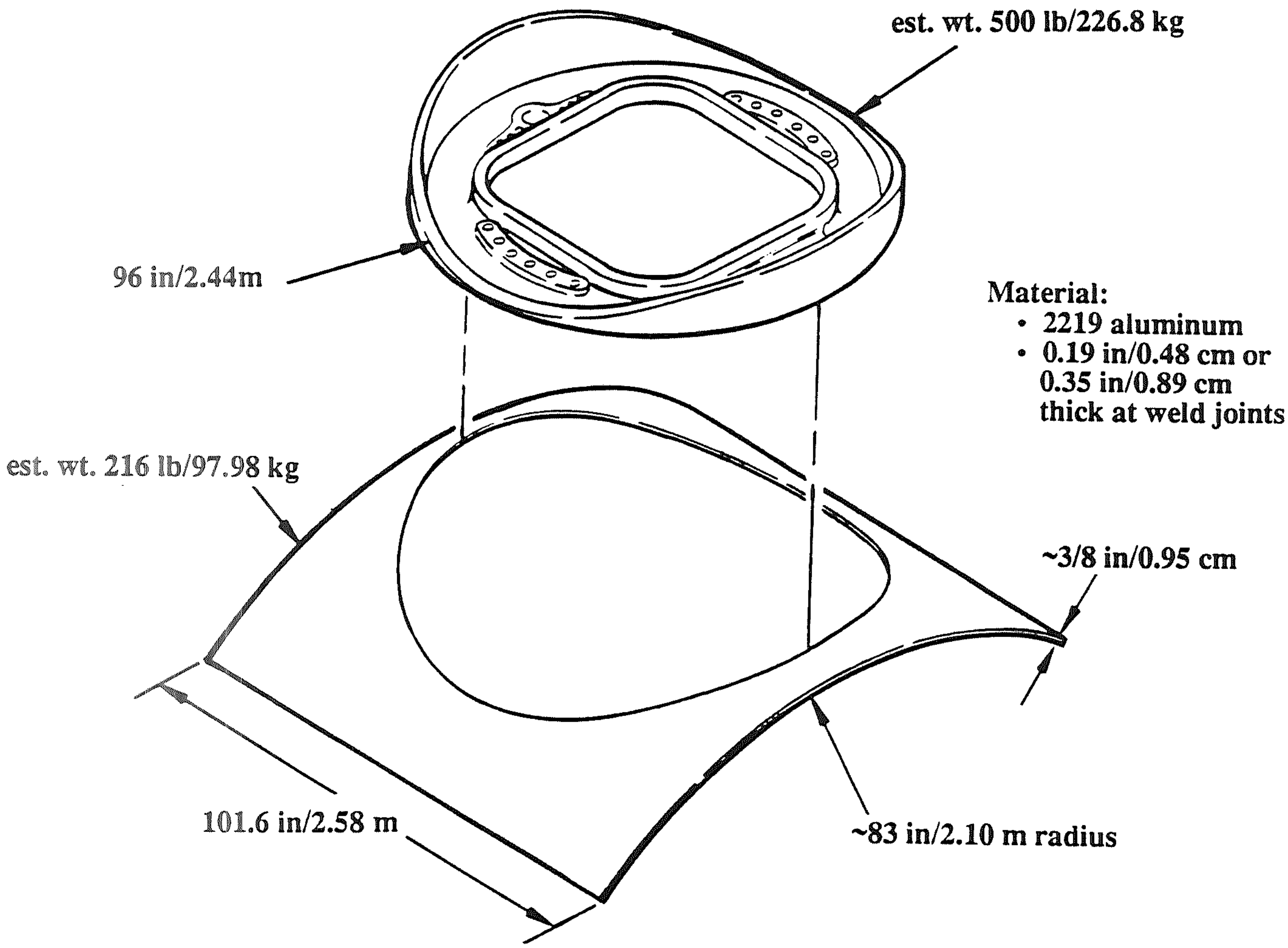

Figure 1. Node Radial Docking Port (Saddle Weld)

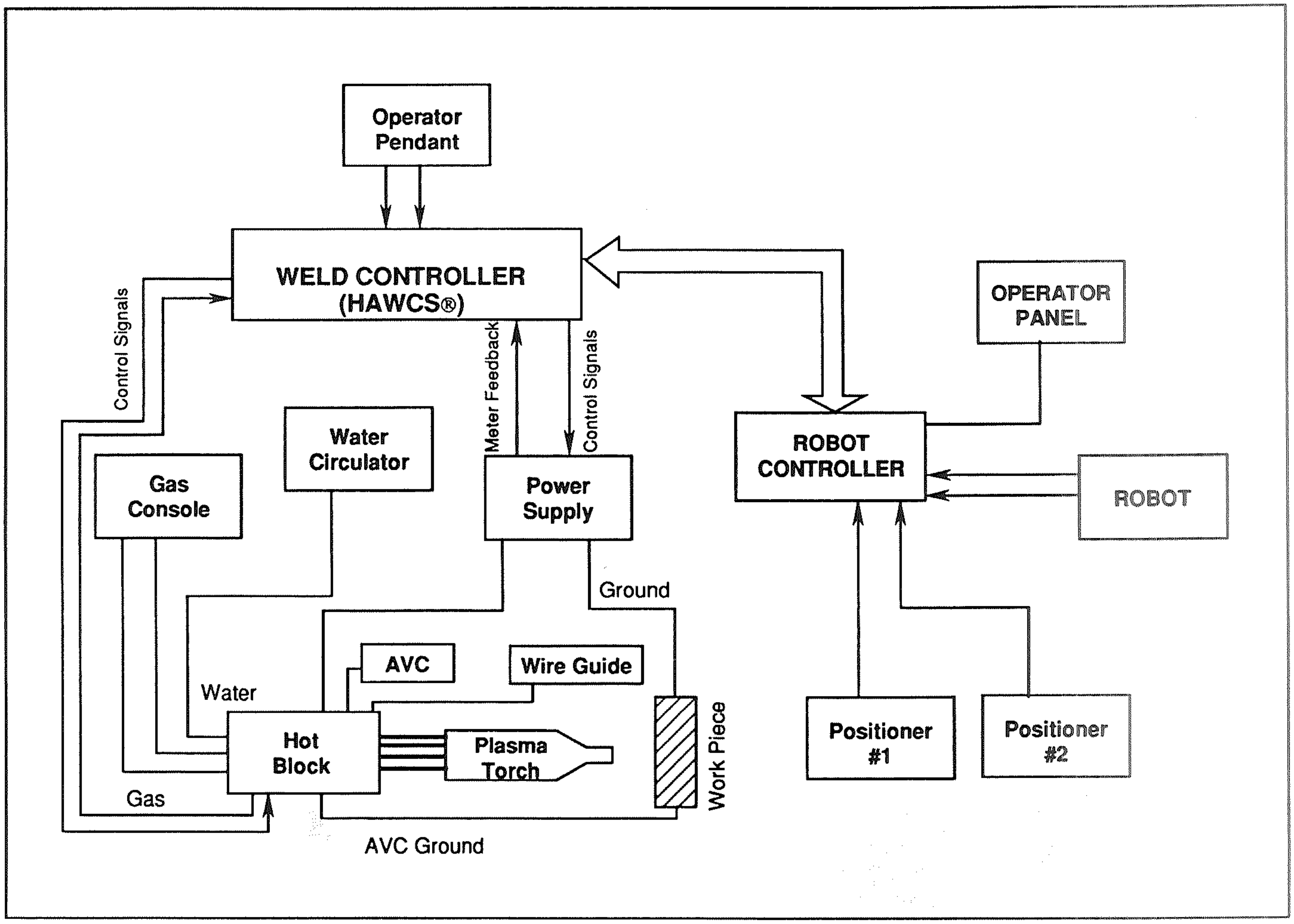

Figure 2. Schematic Diagram of the VPPA Welding System

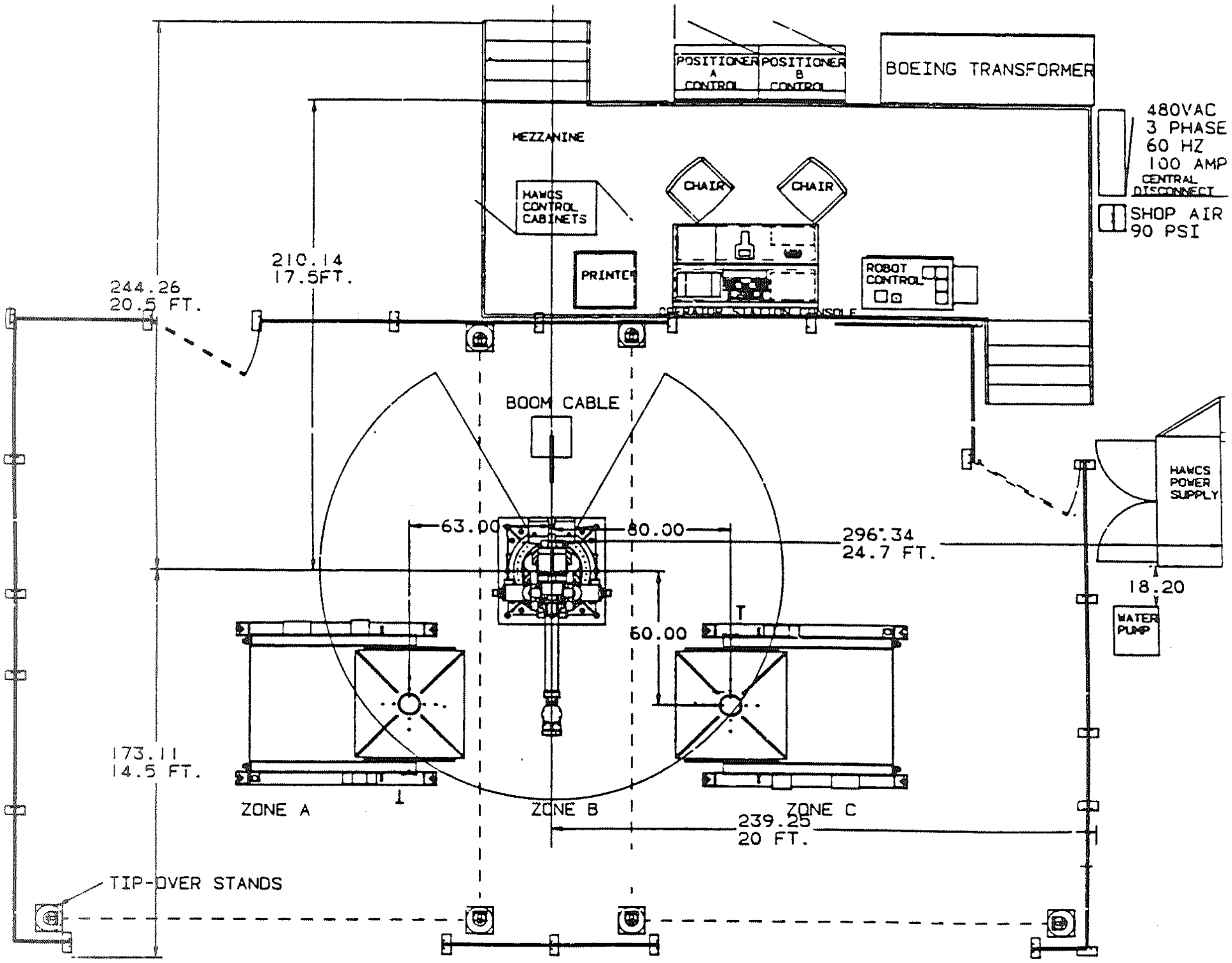

Figure 3. Workcell Layout

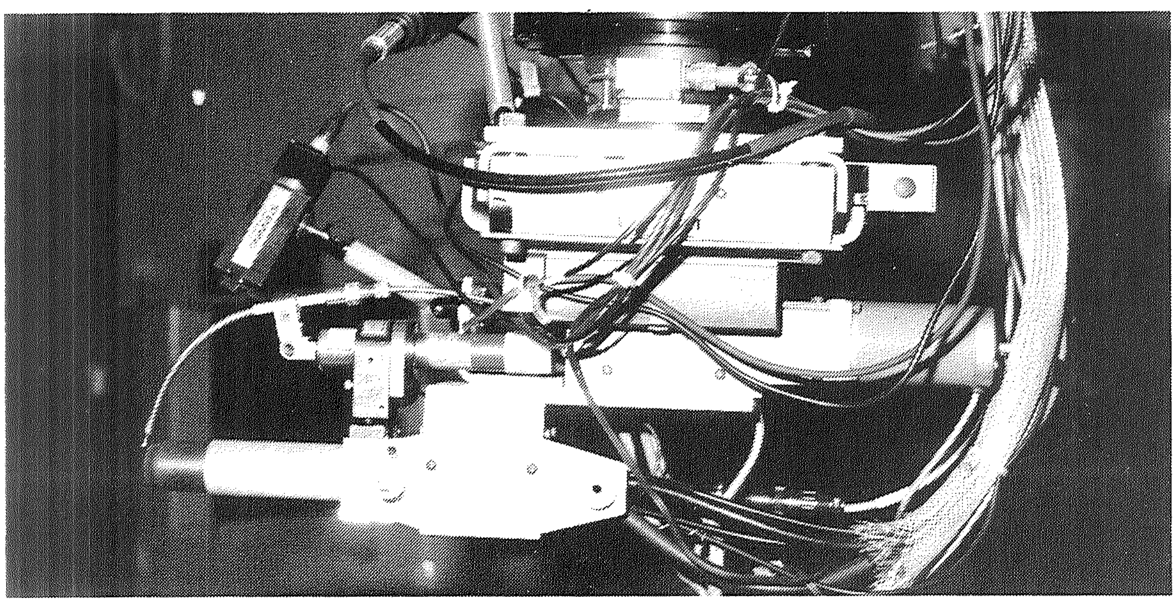

Figure 4. Robot End Effector Tooling

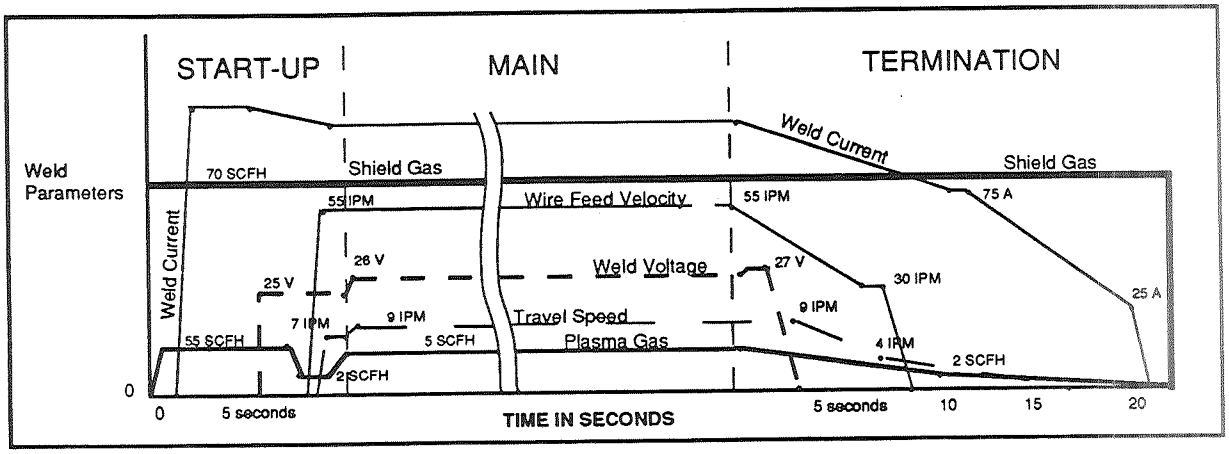

Figure 5. Weld Program Sequence

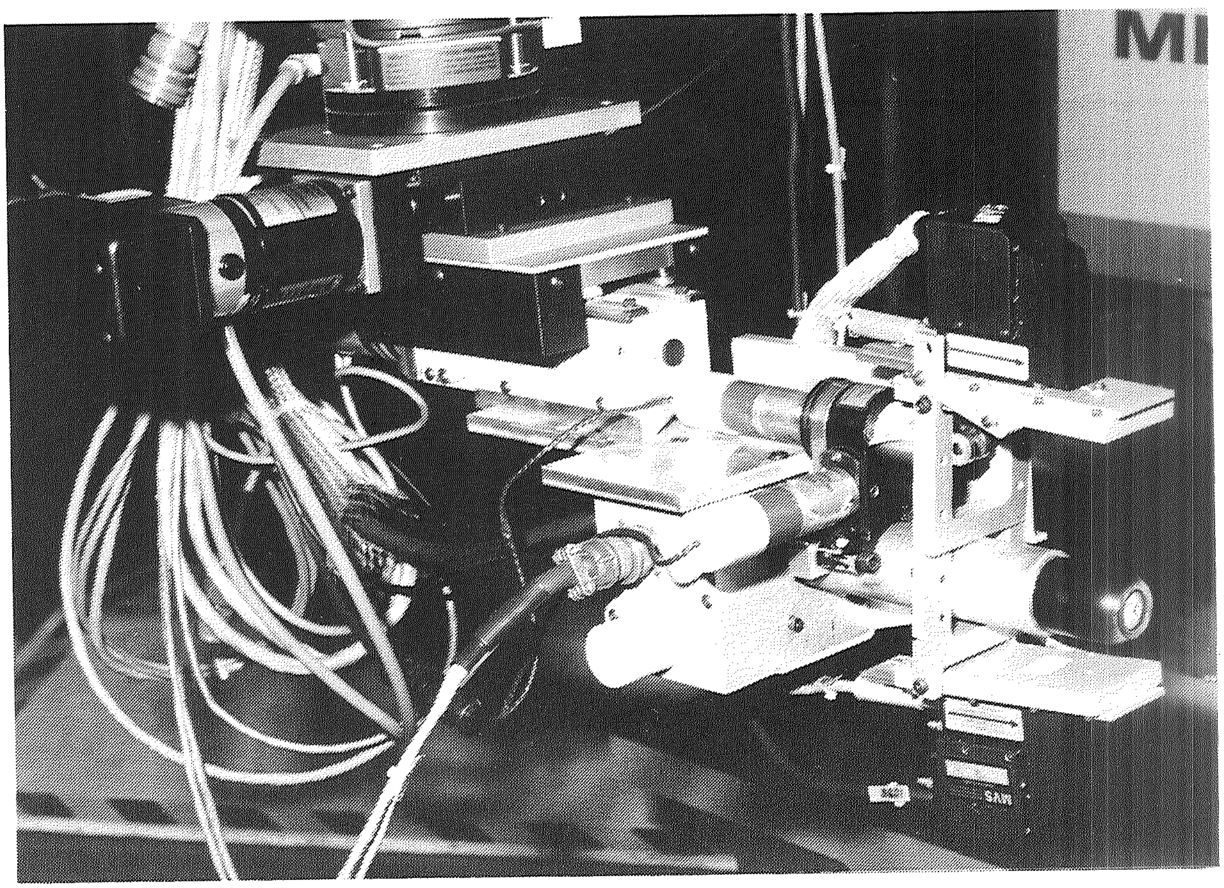

Figure 6. Seam Tracking and Bead Profiling System Mounting

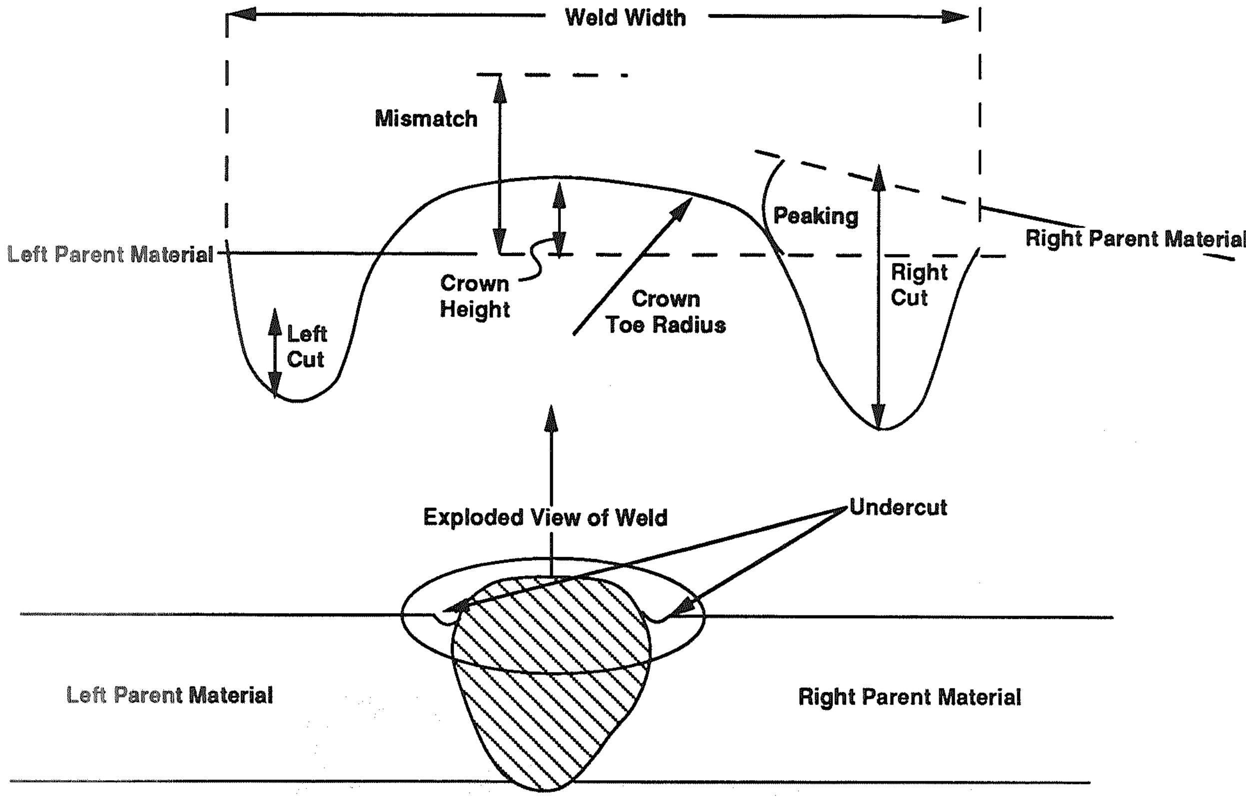

Figure 7. Weld Bead Parameters