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WELDING THE SPACE STATION COMMON MODULE PROTOTYPE

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The American Space Station will contain a group of thin-walled aluminum pressure vessels providing habitable space for our astronauts to live and work. These vessels will be fabricated by welding with computer controlled precision-welding equipment utilizing the variable polarity plasma arc welding process (VPPAW) just as the prototype vessel was by The Boeing Company.

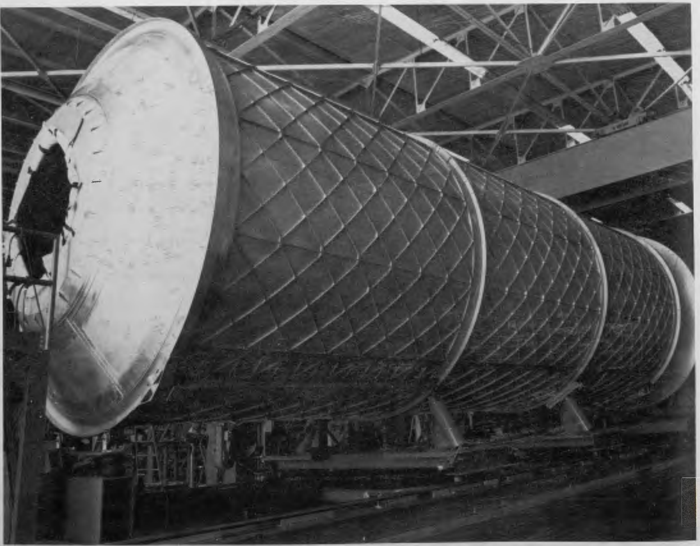

Figure 1 Prototype Of The American Space Station Common Module On The Girth Welding Fixture At NASA-MSFC, Huntsville, Alabama.

Introduction

The NASA Manned Space Flight program planned for the 1990's is directed towards the commercial use of space through development of large space structures serving a variety of missions. The diversity of the program, and the demands of the mission tasks requires a thorough understanding of the mission requirements and the requirements for subsystems which are readily adaptable to a wide range of applications.

The heart of the NASA Space Station is the common module; a light weight, thin walled pressure vessel that can be configured for a wide range of functions: i.e., laboratories, manufacturing facilities, living quarters, and cargo carriers. Before the space station is placed in orbit, development articles must be built and tested, design issues must be resolved, manufacturing problems overcome and accurate cost information generated.

The Boeing Aerospace Company was recently awarded a contract to build the modules, the node structures connecting the modules, the environmental control and life support system, and the thermal control and audio-visual systems for the American Space Station.

In late 1984, the Boeing Aerospace Company's Space Systems Division funded a multi million dollar research development program to design and manufacture a prototype structure, aimed at resolving a number of questions relative to the status of existing technology and demonstrate a manufacturing readiness position. The many faceted benefits of the program included:

1) Development of fabrication sources for production hardware components.

2) Validation of design concepts,

3) Validation of manufacturing concepts,

4) Providing a test bed for Boeing and NASA engineers

5) Development of credible manufacturing and cost data,

6) Development of a working relationship between Boeing and NASA engineers.

This program was carried out in conjunction with the phase B Preliminary Space Station engineering studies contract and in close cooperation with NASA-MSFC whose experts from the productivity center provided technical counsel and guidance. NASA-MSFC provided a manufacturing area where tooling and welding equipment were installed and Boeing engineers, welders and other manufacturing personnel fabricated a prototype of the space station common module. The prototype is a 2219 aluminum, thin wall pressure vessel that was welded by a state-of-the-art computer controlled, variable polarity plasma arc welding (VPPAW) process. The first production level weld was completed in May, 1986, and the final close out weld completed in March 1987. During the ensuing time period, more than 7000 inches of spaceflight quality welds were made with a defect rate of less than one percent.

Prototype Design

The common module prototype is a thin walled aluminum pressure vessel measuring 13.67 feet in diameter by 43.6 feet in length (figure 1). The welded design is based on five basic elements:

1) Skins
2) Ring Frames
3) Gore Sections
4) Docking Port
5 Window Frame

Additional components which are mechanically attached to the completed weldment include longerons, trunnion, and keel pins and fittings.

The structural material is 2219 aluminum in the size and temper shown in Table I. The width of the skin plates and the thickness of the ring forgings were outside the normal standard mill capabilities, consequently special processing controls were required to produce the material. The heat treat condition of the plate selected for the docking port was dictated by cost and material availability.

In addition, the physical size of the components and their configurations severely limited the sources available to produce the various components; accomplishing the manufacturing processes of forging, machining, heat treating and chemical processing.

The skins (figure 2) which were welded together to form the three shell structures are of an external waffle grid design 0.125 inches thick in the membrane section, 0.190 inches thick at the weld lands with 0.100 inch thick ribs, 0.875 inches high. The skins were machined in the flat then contoured by brake forming followed by age forming to establish the final contour.

The sixteen gore sections (figure 3) were also machined in the flat to 0.125 inches in the membrane section and to 0.350 at the weld lands. They were then contoured by brake forming followed by age forming.

The four ring frames (figure 4) were ring rolled as a two-high ring forgings which were then cut into two rings after heat treating. The finished parts are basically on I beam cross section-with stubs protruding on either side of the centerline which mated up to the cylinders and the gore assemblies. The stubs extended sufficiently beyond the flange of the I to permit the welding torch to clear.

The two docking ports (figure 5) were rough machined then solution heat treated and aged before final machining. The cross section varies from about two inches in thickness about the 50 inch square opening to .350 at the outer edge.

The window frame (figure 6) was rough machined, aged then finish machined to the required configuration.

All weld joints were square groove and the weld beads were left on.

The structure was conversion coated either at the detail or subassembly level by dipping then finished by hand after welding.

TABLE I

COMMON MODULE PROTOTYPE - MATERIALS OF CONSTRUCTION (WELDMENT ONLY)

Component	Type And Purchased Temper	Size
Skins	2219-T37 Plate	1.25" x 140" x 154"
Ring Frames	2219-T852 Rolled Ring Forging	174 Inch OD x 7.35" Wide by 6.75" High
Gore Sections	2219-T351 Plate	.375" x 48" x 72"
Docking Port	2219-0 Plate	5.5" x 100" x 100"
Window	2219-T351 Plate	6.0" x 51" x 60"

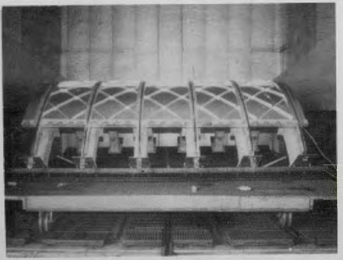

Figure 2

Typical waffle grid skin section mounted in restraint aging fixture. The final part contour is achieved during the precipitation hardening process.

Figure 3

Gore segment - eight gore segments are welded together to form the truncated cone shaped section of the bulkhead assembly.

Figure 4

End ring frame being readied for welding to the aft end of the gore assembly.

Figure 5

Docking port - machined from a 5-1/2 inch thick plate 100-inches square. The opening is 52-inches square.

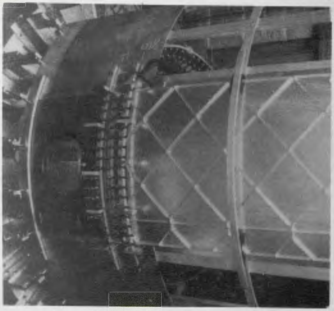

Figure 6

Window frame readied for welding to skin section in the girth weld fixture.

Material of Construction

The common module prototype is fabricated from 2219 aluminum which was developed in 1954 for high temperature applications. 2219 is a readily weldable copper alloy having a nominal composition of 6.3% Cu, 0.3% Mn, 0.06% Ti, 0.10% V and 0.18% Zr. When solution heat treated, cold worked and aged, ultimate tensile strengths approach 70 ksi. 2319 aluminum alloy which is of similar chemistry with .0008% beryllium and 0.15% titanium, is the filler material used for welding. In the as-welded condition (including the weld reinforcement) an average weld strength above 40 ksi is obtained and qualified per NASA MSFC-SPEC-504B(1).

The first 2219 aluminum pressure vessel application (1959-1963) was for the fuel tank of the Bomarc B surface-to-air missile (2) where it replaced 2014 aluminum and 6061 used on the earlier Bomarc A Missile. Subsequently, Boeing and NASA-MSFC selected it for the Saturn S1-C fuel and lox tanks (3); the first stage of the powerful Saturn V Rocket. It has since been used by NASA for diverse space hardware such as the frame of the Lunar Rover, cryogenic tanks for the Manned Orbiting Laboratory, high pressure hydrogen and helium bottles for the Viking 1973 Lander and more recently the Space Shuttle's Crew Module (4) and External Tank (5).

Welding Process

The variable polarity plasma arc welding process (VPPAW) is rapidly becoming the work horse process for welding aluminum space hardware. This process as it exists today has been developed and refined over a 16 year period. While plasma arc welding in the keyhole mode had become a recognized process for welding many materials during the 1960's, it's application to aluminum had repeatedly lead to failure. In 1972, Boeing Aerospace Company's manufacturing technology staff began indepth studies to apply the process to aluminum. Van Cleave's studies (6) identified several key factors that lead to the breakthrough in the application of PAW to aluminum. The two primary factors were:

1) Independent control of the straight and reverse polarity amperage were required to provide the appropriate heat and cathodic cleaning relationships

2) The time ratio (in milliseconds) of the alternating straight and reverse polarities was critical

Engineers at Hobart Brothers supported the process development and developed the required power sources.

By 1974, baseline welding variables had been established for 1/4 inch 2219-T87 in the flat position. Following the initial development effort subsequent studies applied the process to a range of thicknesses of 2219-T87, 5456-H116, 5086-H32, 6061-T6 and A356 cast alloy.

Boeing implemented the variable polarity plasma arc welding (VPPAW) for the welding of twenty-seven (27) U. S. Army Roland missile firing units from 1979 to 1982, joining 5086 or 6061 plate to A356-T6 castings ranging from 3/16 to 5/16 inch in thickness.

The manufacturing welding organization at NASA-MSFC began working with the process in 1979 with the firm objective of utilizing it for the fabrication of the Space Shuttle external tank. This development resulted in a series of achievements that significantly extended the capability of the process including:

1) Refinement of the Hobart Brothers power supplies,

2) Development of a programmable welding control system by General Digital Industries (GDI) of Huntsville, Alabama.

3) Development of a high performance plasma torch produced by B&B Precision Machine, Inc. Brownsboro, Alabama,

4) Development of an extensive engineeing data base on VPPAW welded 2219.

Figure 7

Welding power supply including computer controller and printer. A complete record of essential welding variables is made every 5 seconds during the welding cycle.

Figure 7 is an overall view of the power supply and computer, and figure 8 is a close-up view of the computer screen. The computer is programmed to control the arc voltage, current, wire feed rate, travel speed and gas flow rates and distance traveled, within limits specified by the weld procedure. This capability permits engineers to program a complete weld cycle including starts and terminations with precisely controlled heat inputs. While not used on this program, this capability would also permit the welding of tapered sections.

Weld schedules are established by welding test panels under closely controlled conditions, then testing specimens cut from the welded panels. The limits of the essential variables are established on the basis of the tensile properties achieved. Once the broad operating limits are established, the engineer is capable of defining trim limits which further restrict the natural variation in the welding parameters that can occur. Once the computer has been programmed, the operator can make adjustments only within the procedure limits of the setting. In actuality, it was found that only the arc current could be permitted to vary; all other parameters were fixed.

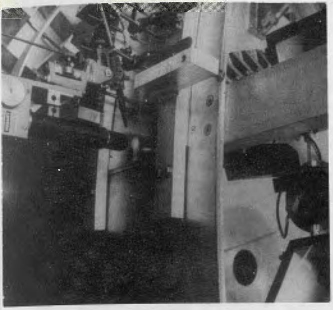

Figure 8

Close-up of welding torch and back side viewing camera. Two welders monitor the welding process. One monitors the control station and the second monitors (via a video camera which also records the operation) the back side as the weld is being made.

Weld Requirements

The engineering prototype program was conducted as close as practical to a production program and welding operations were carried out in strict adherence to the requirements established in the NASA welding specification.(1) A program unique welding specification was prepared which established the controls necessary to assure compliance with the NASA requirements.

As the program matured and as specification deficiencies become apparent, it was ammended such that by the completion of the prototype program the specification would be applicable to a full scale production effort with minimum difficulty.

Unique specification problems that surfaced during the prototype program included:

1) Procedure qualification requirements
    a. Weld starts and termination on girth welds
    b. Main weld schedules
    c. Documentation
    d. Machine tack welding

2) Computer program security

3) Machine weld repair requirements

4) Computer control limits - interpretation of computer print outs

5) Weld procedure criteria.

The MSFC-SPEC-504B requirement for 2219 in the as-welded condition, including the weld reinforcement intact, is 40 ksi average ultimate tensile strength with a 38 ksi minimum.

In the classical sense, as applied by AWS D1.1, AWS D1.2 and the ASTM boiler code, Section IX, welding parameters developed for one gage of a given alloy are applicable to a broad thickness range. However, for precision machine welding with the VPPAW process, it was found that the welding parameters were gage unique and somewhat influenced by the tooling used. Because of this latter influence, verification welds were made to assure that machine settings established with test plates were applciable to the actual hardware.

All welding was in the veritical-up position. However, there were significant differences in the actual weld procedures for the various joints of the same thickness.

Gore to Gore Welds - .350 inch thick

These welds were made in two passes including a penetration and fill passes. Starts and stops were made on run off tabs because the tooling provided rigid clamping. Tack welding was minimal. For these welds the parts were held stationary and the welding torch moved.

Gore Assembly to Docking Port and Ring Frames - .350 thick

These welds were made in three passes: a machine tacking pass, a penetration and a fill pass. The parts were affixed in the girth weld fixture and the mating edges milled in place to provide a precision fit between the parts. Some manual tack welding was done to assure the parts were maintained in a fixed relationship during machine tack welding. For these welds, the part was rotated and the welding torch remained in a fixed position.

The precision control afforded by the computer permitted the development of a procedure for starting and terminating these girth welds so that the required weld properties were achieved at every point along the completed weld.

Window Frame to Skin - .190 inch thick

These welds were made in two passes including a penetration and a fill pass. This weld was made with the parts affixed to the girth weld fixture and rotated during welding. Starts and stops were made on run off tabs.

Skin to Skin Welds - .190 inch thick

These welds were made both with a single pass, or a two pass mode (penetration plus fill), see figure 9. The amount of metal deposited on the fill pass was small relative to that deposited during the penetration pass. Shrinkage across the first weld joints was monitored which permitted adjustments to be made in the fit up of the last joint so that the diameter of the completed cylinders closely matched that of the mating ring frames.

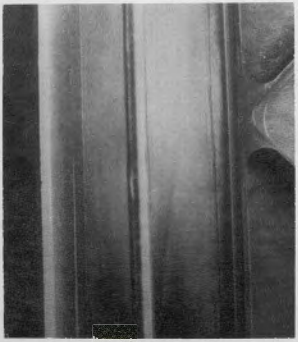

Figure 9

Close-up of seam weld between two skin segments.

Cylinders to Ring Frames - .190 inch thick

These welds were made in a two pass mode, involving a tack pass and a penetration pass close dimensional control was achieved on the overall length of the barrel by monitoring shrinkage across the joints and adjusting trim lengths in the final girth weld.

In each case, welding of each pass was controlled by the computer; the welder initiated the process and made minor adjustments in arc current and the torch position to assure tracking of the weld seam. When making the girth welds a dry run was made to establish the absolute length and tracking of the weld seam. Once this was programmed into the weld schedule, termination of each pass was automatic.

All welds were subject to visual, penetrant and radiographic inspection and found to be virtually defect free.

Assembly Sequence

The prototype was built up in a series of subassemblies the sequence being very close to be followed on the production hardware.

Step 1 Gore Assembly (2)

Each gore assembly is composed of eight segments and is built up by welding four sets of two segments together; then welding these into two 180 degree sections. The 180 degree sections were trimmed to length, then welded together.

Step 2 Bulkhead Assembly (2)

The Bulkhead Assembly is composed of a docking port, gore assembly and a ring frame. The gore assembly was trimmed to mate to the docking port then welded. This subassembly was repositioned in the girth weld fixture and the end ring frame brought into position and welded to the large end of the gore assembly.

Step 3 Window-Skin Subassembly (1)

The Window Frame and short Skin Section were joined by a single weld in the Girth Weld Fixture.

Step 4 Cylinder Assembly (3)

The three cylinders were built up from their respective skin sections. Shrinkage across each weld seam was monitored so that the parts could be trimmed within close tolerances to their mating parts.

The completed end cylinders were trimmed to length (including shrinkage allowance) then an intermediate Ring Frame manually tack welded to the cylinders.

Step 5 Cylinder To Bulkhead Assembly (2)

The end cylinder was mated to the bulkhead assembly and the centerlines trued. Each assembly was completed in one day of welding. The cylinder was welded first to the bulkhead assembly, the welding torch repositioned, and the weld between the cylinder and the intermediate ring frame completed.

Step 6 Final Assembly

The center cylinder was first fitted and welded to one end assembly. This subassembly was then mated with the opposing end and the final seam weld completed. All welds were subject to visual, liquid penetrant and radiographic inspection to the required standards.(1) Less than one percent of the total weld length contained process-type defects requiring repair (porosity, inclusions, undercut, etc.)

Conclusion

Design and fabrication of the common module prototype permitted engineering and manufacturing personnel the opportunity to identify and resolve a large number of technical issues that will be applicable to the production hardware program. In addition to the benefits gained in the manufacturing area, the completed module is a flight quality structure that can be utilized for further engineering studies.

Not all manufacturing problems were resolved during the prototype program because of design and tooling restrictions. However, those remaining will be resolved by design, tooling or process modification when the production program begins. We have already moved far down the learning curve for construction of the Space Station common modules and are confident that the progress will gain momentum as the program hardware begins to take shape.

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