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Advances of orbital gas tungsten arc welding for Brazilian space applications – experimental setup

Abstract: *The present work describes details of the several steps of the technology involved for the orbital Gas Tungsten Arc Welding (GTAW) process of pure commercially titanium tubes. These pieces will be used to connect the several components of the propulsion system of the China-Brazilian Satellite CBERS, and is part of the Brazilian aerospace industry development. The implantation involved the steps of environment control; cut and facing of the base metal; cleaning procedures; piece alignment; choice of the type, geometry and installation of the tungsten electrode; system for the pressure of the purge gas; manual tack welding; choice of the welding parameters; and, finally, the qualification of welding procedures. Three distinct welding programs were studied, using pulsed current with increasing speed, continuous current and pulsed current with decreasing amperage levels. The results showed that the high quality criteria required to the aerospace segment is such that usual welding operations must be carefully designed and executed. The three welding developed programs generated welds free of defects and with adequate morphology, allowing to select the condition that better fits the Brazilian aerospace segment, and to be implanted in the welding of the CBERS Satellite Propulsion System.*

Keywords: *Orbital GTA welding, Titanium, Satellite.*

INTRODUCTION

During the 1980's, the National Institute of Space Research (INPE, acronym in Portuguese) began developing priority programs such as CBERS (China-Brazil Earth Resources Satellite), which is a cooperative effort between the Brazilian and the Chinese governments. One of the features of CBERS is its stabilization on three axes. This occurs because of a positioning control known as the propulsion system. This is constituted of four fuel storage tanks (hydrazine), sixteen 1 N micro thrusters and two of 20 N, valves and filters, amongst others, as well as distribution lines made out of commercially pure titanium – grade 2 – to interconnect the various components. Maintaining the positioning of the satellite during orbit depends basically on this system. An eventual fuel leakage from its welds would compromise the entire mission. For this reason, the quality criteria regarding the welding of its components are extremely rigorous and follow the Chinese manufacturing standards for the aerospace sector. With the objective of integrating and testing CBERS, INPE/LIT invested approximately US\$ 220,000 to implant a welding laboratory furnished with equipment for controlling environmental conditions, cleaning and welding of components to be used in the aforementioned satellite by means of the Orbital GTAW process.

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For illustration purposes, Fig. 1 to 4 are representative of the integration of the CBERS Satellite, carried out in the facilities of INPE/LIT by the authors of this study. It is important to point out that these operations were carried out immediately after the stages of experimental setup, qualification and characterization of the welded joints. The success of the project (a rejection indices of only 0,7%) is attributed to the manufacturing procedures developed for handling, cutting, facing, pickling, tacking, welding, internal purging and the use of standardized electrodes and samples during welding operation. Simultaneously, the use of gases with special characteristics associated with filters, rigorous environment control and leak tests were decisive in increasing the quality of the final product.

Considerations regarding titanium and its alloys

Titanium is used in its commercially pure grades or in combination with other elements known as alloys. It possesses unique characteristics, which are responsible for stimulating the extensive interest of a wide range of industrial segments, in particular, the aerospace industry that first used titanium components in airplanes and afterwards in spacecraft. Commercially pure titanium is used in situations of elevated resistance to corrosion associated with forming. Although the 300 series stainless steel has similar characteristics and is significantly cheaper,



Figure 1: Measuring the internal pressure.



Figure 3: GTAW operation.



Figure 2: Manual tack welding operation.



Figure 4: GTAW operation.

its use in the aerospace industry is limited because of its greater density.

Boyer (1996) shows there is around a 50% reduction in structural weight when titanium and its alloys are used as opposed to conventional alloys. Another interesting metallurgic characteristic of titanium and its alloys is the corrosion resistance levels of the base metal on the welded joints. The oxide responsible for the high index of this parameter forms equally on welds as it does on the base metal and results in analogous performance independently of the environment to which they are exposed (Smith, Threadgill and Gittos, 2009).

The commercially pure titanium (CPTi) is 99 to 99.5%Ti, and also contains iron and some interstitial elements classified as impurities, such as hydrogen, nitrogen, carbon, and the most important of all, oxygen, with which it has great chemical affinity. The CPTi is available in several grades depending on their chemical composition. Though present in small quantities, these elements exert a strong influence on the mechanical properties of titanium; oxygen and nitrogen exert a great extent, while iron and carbon have a lesser impact (AWS, 1984; Boyer, Welsh and Collings, 1998; Lathabai, Jarvis and Barton, 2001). The CPTi alloys (grades 1 to 4) display good weldability as they have low coefficients of thermal conductivity and linear thermal expansion, which facilitate the welding operation. They are used in applications in which mechanical resistance is not the highest requirement, unlike resistance to corrosion associated with high ductility (AWS, 1984; Boyer, Welsh and Collings, 1998).

In the CBERS Satellite specifically, the use of titanium is restricted to the propulsion system, in other words, the ultra high purity lines of the hydrazine circuit. Basically, the setup consists of several components interconnected by small diameter tubes. Its joints are connected using the Orbital GTAW process due to the extreme demands regarding the quality of the final product.

Considerations regarding Orbital GTA welding

Orbital welding systems are made up of a programmable power supply, an orbital weld head, electric cables, gas hoses and optional accessories. The power supply is a portable, fully programmable piece of equipment whose welding sequence is controlled by means of a microprocessor. This allows one to adjust different levels for the welding variations according to the diameter, thickness and material to be welded. Precision in relation to the welding parameters is in the order of $\pm 1\%$. The welding machine allows one to program the parameters such as the welding speed and the amperage, either continuous or pulsed (Morgan and

Henon, 1999; Henon, n.d.). Power supplies up to 150 A only use continuous current. Such situations are designed for autogenous welding where filler metal is not used. In general, it is applied when joining small outside diameter tubes (3.2 mm a 177.8 mm) and limited to a maximum thickness of 3.9 mm. The welding is carried out in one step on square butt joints, whose typical configuration can be seen in Fig. 5 (Morgan and Henon, 1999; Brond and Henon, 1996).

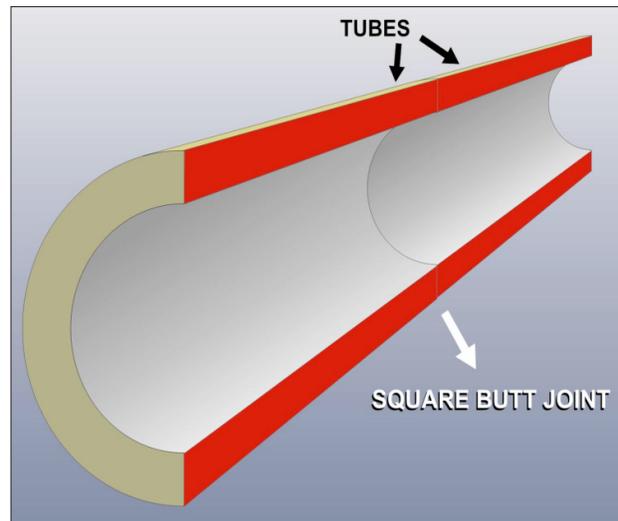


Figure 5: Joint configuration.

MATERIALS AND METHODS

The initial phase of the work consisted of creating a welding laboratory capable of meeting the manufacturing requirements of the very high purity propulsion system of the CBERS Satellite. In this type of setup, the use of a clean room with precise humidity, temperature and particulate control is absolutely necessary. The specified values for the above mentioned parameters are achieved by installing appropriate filters and curtains to purify the air in the working environment.

Next, there was the purchasing of equipment to provide continuity for the manufacturing stages. Firstly, the equipment for the final cleaning of the components, the particulate counter, equipment for facing the tubes and finally the Orbital GTAW power supply for joining the propulsion system components.

The base metal used was imported commercially pure titanium – grade 2 – in the form of seamless tubes, fittings (union cross, tees and spherical connections) and components (filters, valves, transducers etc.) with a diameter and wall thickness equal to 6.0 ± 0.1 mm and 1.0 ± 0.05 mm, respectively. The consumables used were an EWCe-2 electrode (2% cerium tungsten) with a diameter of 1.6 mm and a tip geometry with an angle of 30° and high purity argon gas (99.999%) for shielding and purging.

The success of the orbital technology applied to the aerospace sector is as much a function of the programming of the primary welding parameters, as it is of a series of defining conditions, which together add consistency and quality to the results (Serafin, n.d.; Orłowski, n.d.). In this manner, because of the great number of variables involved in the preparation stages of the base metal and the welding itself, the following sequence of events, described below and presented in the results and discussion sections, was established: environment control; base metal preparation (selecting, cutting and facing); cleaning procedure; alignment; tungsten electrode – type, geometry, dimensions and installation; purging gas pressure control; manual tacking; surveying of the welding parameters; and welding qualification procedure.

Three welding programs using constant and clockwise rotation were separately developed to join the commercially pure titanium tubes, as follows: pulsed current with increasing speed (#A), continuous current (#B) and pulsed current with decreasing amperage levels (#C). Additional data referring to the operational process and to the used material were obtained by consulting specific standards (AWS, 2000; AMS, 1991).

After the welding cycles, the welds were visually inspected (outside and inside) to see if the weld adhered to the criteria established by the Chinese Standards (CAST, n.d.). Three weld beads were selected, each one of which corresponded to one of the programs, in other words, constant (#B), pulsed current with increasing speed (#A) and, finally, pulsed current with decreasing amperage levels (#C).

Once the welding parameters were determined, nine test specimens were welded for each one of the welding programs being studied, and were submitted to visual inspection, radiography and leak tests. The welded joints were cut and the width of the face and root of the weld beads were measured. The evaluation of the welded joints regarding mechanical tests and metallurgic characteristics will be the subject of a future publication.

RESULTS AND DISCUSSION

This part of the work presents the deployment of titanium welding technology in the Brazilian aerospace industry, including the preparatory steps involved in setting up the laboratories, preparing the welding, determining the procedures for welding and inspection of the welded joints.

Control of environmental conditions

The manufacturing cycle of ultra-high-purity systems of which welding is a fundamental part, requires precise control, not only of its stages, but also of the environment in which

it is manufactured. In this sense, the Welding Laboratory at INPE/LIT is specifically equipped for this purpose, capable of maintaining humidity between the ranges of 40 to 50%, temperature between 18 and 22°C and particulate control of 10,000, as required by the Chinese Specifications.

Preparation of base metal (selecting, cutting and facing)

Due to the rigorous standards applied to weld bead quality, the presence of gap between components to be welded is a reason for rejection in accordance with aerospace procedures. Equally, deformities, out-of-roundness and variations of thickness along the joints are responsible for causing inconsistencies (Mannion and Heinzman, 1999a; Mannion and Heinzman, 1999c). Based on such information, strict control is necessary, related to material specification such as dimensional tolerances, as well as the preparation of the joints and the obligatory facing of appropriate equipment. The tubes were cut into appropriate lengths, which was followed by the facing of both extremities with respect to perpendicularity requirements (< 0.02 mm), section roundness (< 0.05 mm), absences of deburring and beveling of the edges. Argon gas was then injected into the tubes to remove residues left over from the above operations. When facing was completed, the edges were deburred and configured for welding.

Cleaning procedures

Firstly, chemical pickling is carried out to remove the oxide layer. Initial tests establish the average time for immersing the test specimens in successive acid solutions baths (70% nitric acid, 50% hydrofluoric acid and water with distinct fractions of 15, 3 and 82 parts per volume, respectively). Next, the test specimens were transferred to an oven for drying, where they remained for 2 hours at a temperature of 50 to 60°C. Following this, the parts were placed in plastic bags filled with argon (99.999%) so as to eliminate any possible form of contamination.

Final cleaning (or internal cleaning) consists of circulating isopropyl alcohol through the insides of the tubes while connected to a machine of 99.995% pure gaseous nitrogen and at a pressure of 1.5±0.5 bar. The machine contains vacuum filters at several points of the cleaning system, which allows samples of liquid to be collected on membrane filters throughout the process and analyzed under an optical microscope using particle counting techniques. The purpose of this operation is to verify the degree of cleanliness. Once the pre-established criteria have been achieved, regarding the dimension of particles, the cycle is interrupted and the drying of the components at a temperature of 60±5°C begins. After this stage, the tubes are placed in plastic bags filled with argon

(99.999% pure) and duly identified. Figure 6 outlines the equipment used.

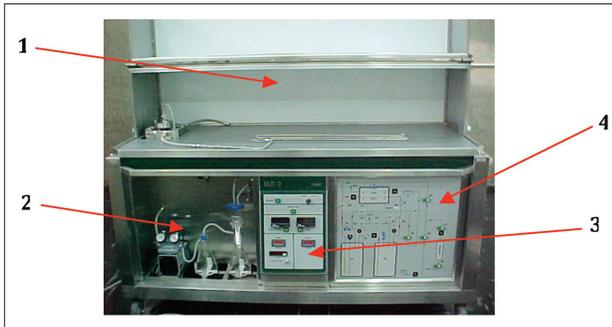


Figure 6: Final cleaning equipment. (1) cleaning and drying compartment; (2) samples collecting circuit for analysis; (3) equipment controls; (4) cleaning circuit.

Alignment

For orbital systems, the precision of alignment between the parts to be welded is of considerable importance, regarding the quality of the weld beads. Should there be any internal projections as a result of improper settings; these can interfere in the flow of fluids (hydrazine) or, in extreme cases, require reworking (Mannion and Heinzman, 1999b; Mannion and Heinzman, 1999c). For this purpose, a stainless steel alignment gauge was developed to overcome this short-coming. The model consists of two parts, each of which has a groove on its inner part so as to line up the tubes, as seen in Fig. 7. The four external screws help in securing the tubes while the central ones guarantee the correct positioning. The side openings of 180° facilitate the welder’s view of the joint and consequently the manual tacking operation.

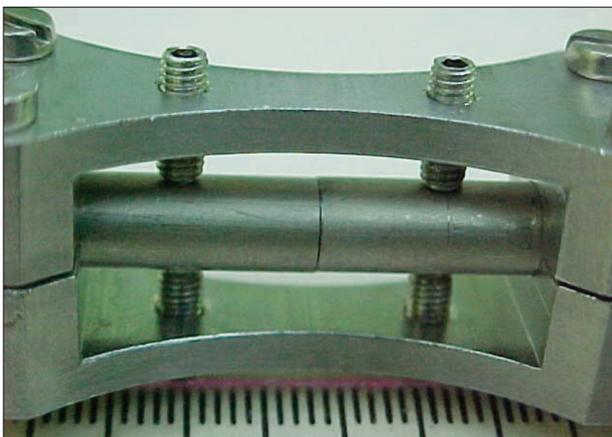


Figure 7: Alignment gauge.

Tungsten electrode - type, geometry, dimensions and installation

The choice of material, its geometry and the electrode dimensions should follow the manufacturer’s

recommendations (Arc Machines, Inc., 1991). The values are calculated in function of the tube to be welded and the model of the orbital weld head.

Control of purging gas pressure

The technique for pressurization consists of establishing a positive pressure inside the parts by supplying purging gas under a constant pressure. Its value depends on the tube diameter, the position of the joint, pressure losses and an airtight purge plug with a small diameter exit orifice to restrict the escape of gas (Henon and White, n.d.). This practice allows one to control the geometry of the weld bead and avoids the occurrence of discontinuities. The equipment used in this process consists of a Magnehelic® (Dwyer Instruments, Inc., USA) pressure gauge and a small T device, both shown in Fig. 8. The determination of the correct working pressure involves the insertion of the small T device into the joint to be welded. Two of its extremities are connected to the network, while the third is fixed to the Magnehelic® gauge.



Figure 8: Magnehelic gauge.

After reading the pressure, the device is removed from the system and substituted by the orbital weld head, and the welding is accomplished. The pressure is the result of the internal tube diameter (ID) purge gas flow rate and the size of the restriction orifice purge plug used at the end. The

difference in pressure is adjusted by increasing or decreasing the flow rate. The working pressure should be sufficient so as to produce weld beads with the same profile as the tube walls.

Manual tacking

This is necessary for maintaining the parts in position. This operation is executed manually using a GTAW torch without filler metal. The dimension of the tacks must be minimum, however sufficiently resistant to keep the joint aligned. The use of purging gas is recommended when tacking, because as well as preventing oxidation of the inner tube, it helps in cooling. The welding parameters are set out in Table 1.

Table 1: Manual tack welding operation

Parameters	Values
Pre purge arc gas time (s)	5,0
Post purge arc gas time (s)	20,0
Upslope current time (s)	0,0
Downslope current time (s)	2,5
Pulse (ON/OFF)	ON
Peak current (A)	38,0
Background current (A)	10,0
Peak current time (s)	0,1
Background current time (s)	0,1
Others parameters	
Arc gap (mm)	1,0
Arc gas flow (l/min)	6,5
Back up gas flow (l/min)	3,2

Survey of welding parameters

The welding parameters for the three programs (#A), (#B) and (#C) are presented in Table 2. It can be observed that, for each of the programs, the nine test specimens produced flat, smooth welds which are of homogeneous width around their perimeters and are devoid of oxidation or other defects on the outside and inside diameters. Figure 9 shows the welding of the test specimens together with the respective equipment, power supply, orbital head and pressure gauge. Programs #A and #C displayed similar characteristics, considering the employment of pulsating current associated with the reduction in the heat input due to an increase in welding speed (#A) and the reduction in amperage (#C) throughout the respective welding cycles. Both procedures are widely used in joining small diameter tubes, so as to minimize the accumulative effects of the energy from welding, particularly in the final phase of the welding cycle (Kou and Le, 1984). In this manner, the presence of concave welds or even perforations – defects generally associated with excesses of energy – can be restricted or avoided.

Despite the fact that specialized literature (Kou and Le, 1984; Henon, n.d.) recommends the use of the above mentioned techniques for welding of small diameter tubes, program

Table 2: Welding parameters for three programs

Welding Parameters	Welding Programs		
	#A (Pulsed current increase the RPM levels)	#B (Continuous Current)	#C (Pulsed current decrease the amperage levels)
Welding Sequence			
Pre purge arc gas time (s)	70,0	70,0	70,0
Pos purge arc gas time (s)	50,0	90,0	90,0
Upslope time (s)	0,0	0,0	2,0
Downslope time (s)	1,0	1,0	1,5
Delay (s)	1,0	0,8	0,0
Level I (1st Quadrant)			
Pulse (On/Off)	ON	OFF	ON
Travel speed (RPM)	4,0	8,0	7,4
Peak current (A)	25,0	21,0	40,0
Background current (A)	8,0	-	12,0
Peak and background current times (s)	0,1	-	0,1
Level II (2nd Quadrant)			
Pulse (On/Off)	ON	OFF	ON
Travel speed (RPM)	4,0	8,0	7,4
Peak current (A)	25,0	21,0	37,4
Background current (A)	8,0	-	12,0
Peak and background current times (s)	0,1	-	0,1
Level III (3rd Quadrant)			
Pulse (On/Off)	ON	OFF	ON
Travel speed (RPM)	4,0	8,0	7,4
Peak current (A)	25,0	21,0	34,8
Background current (A)	8,0	-	12,0
Peak and background current times (s)	0,1	-	0,1
Level IV (4th Quadrant)			
Pulse (On/Off)	ON	OFF	ON
Travel speed (RPM)	4,0	8,0	7,4
Peak current (A)	25,0	21,0	32,2
Background current (A)	8,0	-	12,0
Peak and background current times (s)	0,1	-	0,1

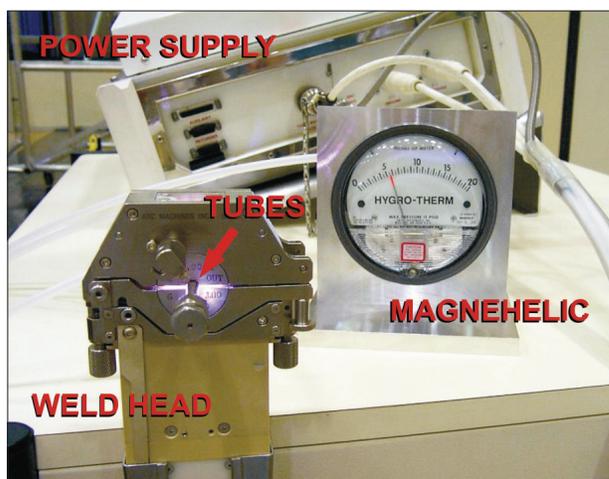


Figure 9: Orbital GTAW operation of the test specimen.

#B used the same heat input for welding the test specimens. The success of the results, like the other programs, can be attributed to the use of the technique of internal pressurization with purging gas. This is responsible for controlling the morphology of the fusion zone, for protecting the molten area and the other heated regions of the tube as well as cooling the part/set (Hennon, n.d.). Table 3 shows the heat input values employed for each of the programs being studied.

This parameter can be defined as being the quantity of energy supplied by the arc to the joint. It was calculated by the expression $HI = f(E \cdot I / v)$, where HI = heat input, E = volts, I = amperes, v = millimeters per second and f is the efficiency of the heat transfer equal to 0.9 for the GTAW process. The voltage readings were obtained by the use of a multimeter whose positive and negative terminals were connected to the tube and orbital weld head rotor, respectively. The average value corresponding to a total of five readings carried out during each of the welding programs was 8.37 V. In such a way, it was

Table 3: Heat Input for three welding programs

Heat Input	HI ₁ (J / mm)	HI ₂ (J / mm)	HI ₃ (J / mm)	HI ₄ (J / mm)
Programs				
#A (pulsed current increase the RPM levels)	108	108	88	88
#B (continuous current)	63	63	63	63
#C (pulsed current decrease the amperage levels)	84	84	76	72

possible to obtain the welding energy values for each level (quadrants) of the programs under test. Increasing values can be observed in the sequence #B, #C and #A. Although programs #A and #C employed pulsating current in their respective cycles, the higher welding energy values can be justified by the low speeds (#A) and high amperages (#C).

Visual and X-ray inspection

Figure 10 shows the typical weld bead from the programs being studied, where it is possible to see the aspect of the face and root. Its principal characteristics are uniformity in width, alignment, total penetration, smooth finishing and no oxidation in the heated regions. All nine weld sets for each of the welding programs are aligned without mismatching. The examination of the internal diameter of the welded joints using a boroscope indicated conformity with the Chinese Quality Standards (CAST, n.d.). X-ray inspection revealed no defects on the welded samples, which were then considered approved.



Figure 10: Weld test coupons.

Table 4 displays the dimensions of the fusion zones of the welding programs under test, a total of five readings per welding program. Increasing average values were recorded for the width of the face and root of the weld beads in the

Table 4: Dimensions of the fusion zones

Programs	#A (Pulsed current increase the RPM levels)	#B (Continuous current)	#C (Pulsed current decrease the amperage levels)
Width			
Average face width (mm)	5,72	5,02	5,46
Standard Deviation	0,083	0,109	0,114
Average root width (mm)	3,94	3,02	3,76
Standard Deviation	0,134	0,164	0,114



following order: program #B, #C and #A, respectively. The increased width of the face and root can be attributed to higher welding energy contribution, as can be seen in Table 3. The maximum width should be inferior to 6.0 mm (CAST, n.d.), which was obtained for all welding programs.

Leak test

According to project data, the minimum prescribed levels for welded joints are 1.0×10^{-7} Pa m³/s. All welded joints achieved this value without presenting signs of leakage and as such were considered approved.

CONCLUSIONS

The following conclusions could be obtained from this study, whose objective was to develop titanium welding techniques using the Orbital GTAW process to join components of the CBERS Satellite Propulsion System:

- it could be concluded that the above welding operations involving control of environmental conditions, cutting and facing of the base metal, cleaning procedures, alignment and type, geometry, dimensions and installation of the tungsten electrode were shown to be effective, as well as being necessary for the success of the welding;
- the technique developed using internal pressurization with purging gas proved to be effective, given the results of the internal morphology of the weld bead and the absence of any defects;
- the device used for manual tacking was effective and guaranteed the strict alignment standards required for welded joints;
- the three welding programs developed produced satisfactory results regarding the non-destructive tests carried out, as did the geometrical characteristics of the weld

bead. One of these will be chosen for welding components of CBERS Satellite Propulsion System after a mechanical and metallurgical examination of the welded joints.

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