WELDING HEAD DEVELOPMENT AND QUALIFICATION FOR SOLAR ARRAY MANUFACTURING FOR SPACE APPLICATIONS

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Abstract. *This paper describes a mechanical head development and the qualification process for solar cell welding, aiming at manufacturing of solar array generators for space applications, using parallel gap resistance welding process with direct current power source. The complete welding equipment is composed of: the mechanical welding head; a personal computer and a control software; a welding pulse generator and monitor (commercial of the shelf equipment); and by a digital magnification system. The control software was developed based on the Labview® platform. Initially, the specified process requirements for solar cell welding for space applications are presented, followed by a description of the developed mechanical welding head and its interfaces with the control system, operational procedures, and the experimental welding parameters determination results. Qualification test specimens were manufactured using the welding head and were submitted to qualification tests. The qualification test results are presented and discussed.*

Keywords*: welding, solar cells, solar arrays, space applications.*

1. Introduction

Most of the modern space applications satellites use solar cells as primary energy source to operate its internal equipment. Generally, the solar cell array constitutes the power generation equipment within the framework of a power subsystem of a satellite or other space application system that require electrical power. A solar cell panel is an array of serial and parallel arrangement of solar cells designed to generate electricity directly from sunlight.

One remarkable characteristic of the development in the energy generation area for space applications is that the requirements imposed by the users for specific missions determined the course of the technological development of components and manufacturing processes [Iles, 1993]. The requirements related to the solar cells electrical interconnections [MIL-S-83776], turned the solar array designers to the parallel gap dc resistance welding process, developed and qualified in the beginning of the seventy decade. The welding process is accomplished by localized fusion of a metal interconnector with the solar cell contacts using resistive heating. The dc resistance welding process applied to solar cells provides: lower cost; high reliability interconnections; thermal fatigue resistance; process repeatability and compatibility with advanced array assembling techniques.

The mechanical welding head presented in this paper is part of a set of equipment, tooling and manufacturing processes developed and qualified under a technological development project aiming at attending the Brazilian market demand of space solar arrays [Vaz, 2002], in accordance with the Brazilian National Space Activities Program (PNAE) [AEB, 1998]. This project was supported by the "Small Companies Technological Innovation Program - PIPE" of "The São Paulo State Foundation for Research – FAPESP".

2. Welding Process Requirements

Foreseen the minimization or, whenever possible, the elimination of defects that could contribute to early on orbit degradation, mal function or failure of components or parts of the solar arrays, the set of requirements, related to the parallel gap dc resistance welding process, summarized in the next paragraph are generally imposed by users for low earth orbit satellite applications [Vaz, 2002].

a) Strength - The solar cell welded interconnector shall withstand a 1.5 N pull strength per interconnector terminal, applied at 180° to the terminal direction;
b) Solar Cell Degradation – the welding process shall not degrade the solar cell short circuit current more than 2%.

c) Thermal Stress - The welded interconnections shall meet the pull strength requirement after having been submitted to 1100 thermal shocks between -70^{o}C and +70^{o}C;

d) Appearance - The welding shall not present evidences of cracks, crunches or burned areas, solar cell metallization delaminating, nor deformation due to excess electrode pressure (indentation higher than 50% of the interconnector thickness);

e) Power Supply - The dc power supply shall be capable to control the welding pulse voltage amplitude and duration time during its ascending ramp, constant period and descending ramp.

These requirements are verified through a set of test specimens that are submitted to a qualification test sequence previously defined in a development and test plan [Vaz, 2002]. The following types of qualification test specimens were manufactured:

a) Solar cell with welded interconnectors, usually named “Cell Integrated Connector - CIC”;
b) Solar Module, composed by a number of serially interconnected solar cells;
c) Small Solar Panel, usually named “Test Coupon”, representative of a full size solar panel;

These test specimens are submitted to the following inspections and tests:

a) Thermal Shock;
b) Thermal Cycling;
c) Visual Inspection;
d) Solar Cell Electrical Performance;
e) Electrical Continuity; and
f) Destructive Pull;

The tests from “c” to “d” are executed before and after the environmental tests “a” and “b”. Test “d” is performed before and after the interconnector welding to the solar cell contacts.

3. Welding Head Description

The developed welding head is a semi-automatic device capable to operate through programmable positioning coordinates and control of its three axis movements using step motors. The welding head is composed of an X-Y table for precise positioning the workpieces to be welded below the pair of parallel electrodes. Once the workpiece is positioned, the device executes the vertical movement of the electrodes head, exerting a controlled pressure over the workpiece. The electrodes have independent vertical movement from each other. The electrodes vertical movements are provided through a cam mechanism powered by a step motor. Figure 1 shows a picture of the developed welding head [Vaz, 2004-a].

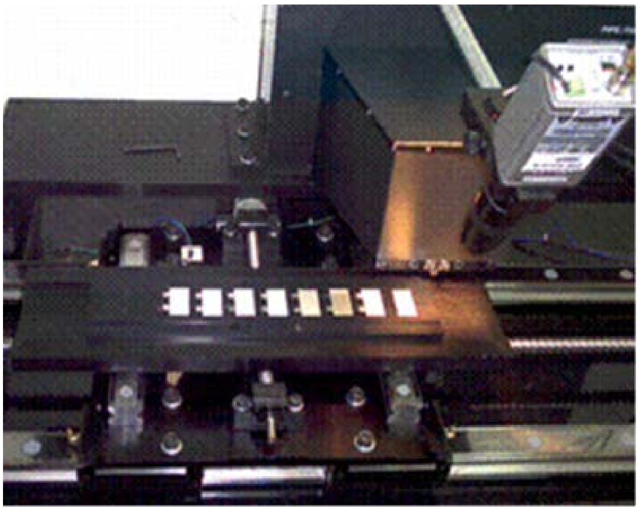

Figure 1: Welding Head picture showing the X-Y table and the electrodes head.

Once the electrodes are positioned in the workpiece, the control program, running in a personal computer, commands the power supply to release the welding electrical pulse. The welding is monitored through a welding monitor. The welding parameters are sent to the control program that verifies if they are inside a previously experimentally established window limits. If the welding parameters are considered accepted, the electrodes are commanded to move-up and the X-Y table is moved to the next welding point. Otherwise, the operator is inquired to repeat the welding pulse or to left it as it is. All welding parameters related to each executed welding point are recorded in the computer for quality assurance purposes. These operations are repeated until the last programmed welding point is executed. After welding execution the X-Y table automatically returns to its home position.

The working area is magnified (50x) in a monitor using a digital camera. The images may be grabbed and saved to the computer hard disk for reporting purposes. The control program was developed using the Labview® platform. The welding head is capable of executing four to six welding points per minute depending on the selected axis velocities.

4. Experimental Welding Parameters Determination

One of the fundamental tasks in the welding process is to find one or more real time welding parameters that can positively assure within certain limits that the welding is good in terms of the potential pull strength of the welded parts.

Weld voltage and current comprise the basic welding electrical parameters. Common measurement techniques include current peak, average and time integration. Weld force and displacement constitute prime mechanical welding parameters. The welding force controls the initial interface resistance between the parts. Displacement monitoring measures the distance that the parts compress into each other during welding and can be used to set a minimum weld strength limit.

In the present work, the following welding parameters were experimentally determined [Vaz, 2003-b]:

a) Electrode force (N);
b) Welding Voltage (V);
c) Voltage rising ramp time interval, t1, (s);
d) Constant voltage time interval, t2, (s);
e) Voltage drop ramp time interval, t3 (s).

The welding parameters were experimentally determined executing 8 welding points per cell in a lot of approximately 50 cells. Each welding point was submitted to visual inspection, solar cell electrical functional condition verification and destructive pull test.

The electrodes forces were experimentally adjusted to get an electrode indentation foot print that meets the requirement described herein in item "2d", through the electrodes foot print visual inspections. The electrodes adjusted force was 4.0 N. The welding voltage was increased in steps of 0.020 V from 0.460 V to a maximum of 0.630 V. The t1, t2 and t3 time intervals were initially set based on preliminary test results, and afterwards increased or decreased based on the pull test results sequence.

Figure 2 shows the experimental test results as a function of the welding voltage, welding electrical charge and the welding rupture force obtained from destructive pull test results, with t1 = 0.080 s; t2 = 0.200 s; and t3 = 0.010 s [Vaz, 2003-b].

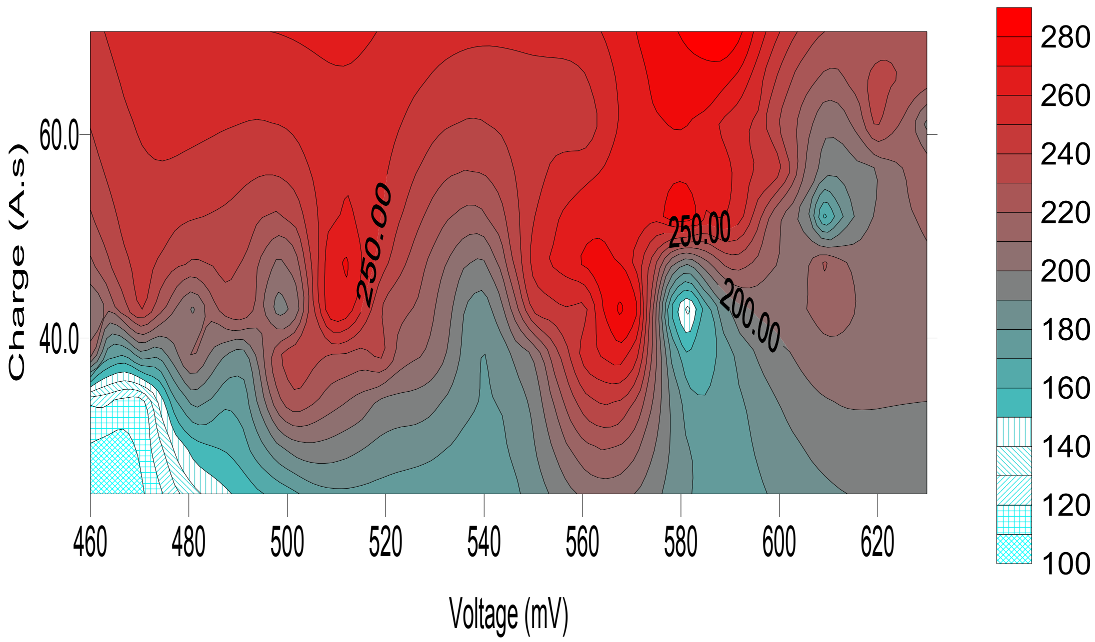

Figure 2: Experimental welding parameters determination test results. Welding voltage (V) as a function of the electrical charge (A.s) and welding rupture force (N x 100).

Figure 3 shows another graphical representation of the same test results shown in Figure 2. As it can be observed from both Fig. 2 and Fig. 3, welding rupture forces higher than 1.5 N are obtained for welding voltages in the interval from 0.490 V to 0.580 V, with charges above 40 A.s. Visual inspections showed the existence of welding burned areas for welding voltages above 0.590 V. It can be observed in Fig.2 and Fig. 3 that the rupture force decreases in the low charge regions, due to low energy level, and also in the high charge regions due to energy excess [Vaz, 2003-b].

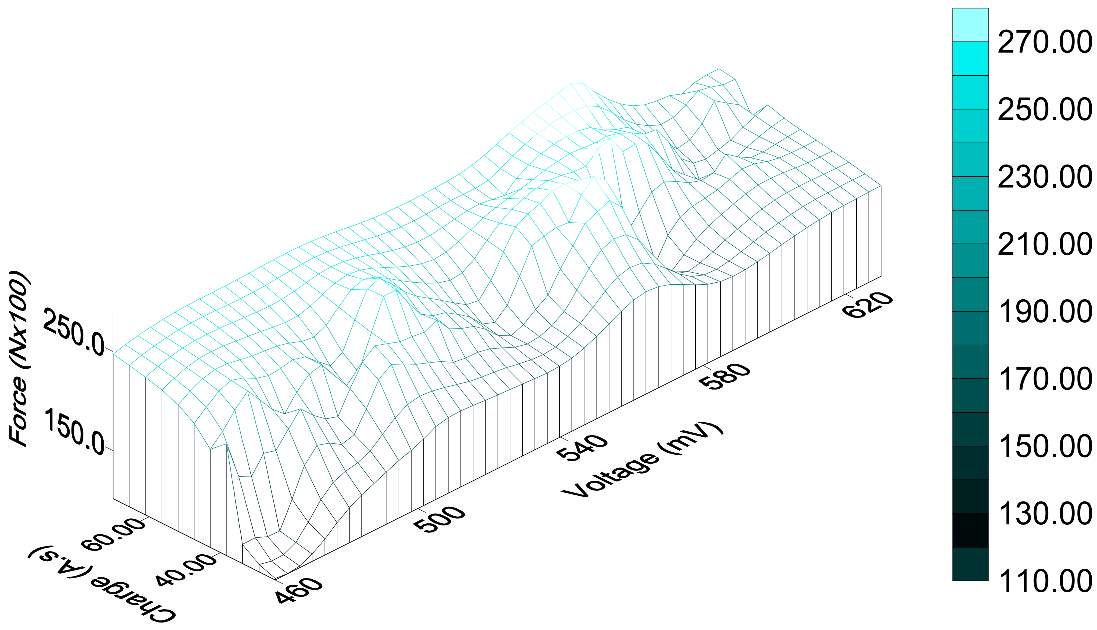

Figure 3: Experimental welding parameters determination test results. Welding voltage (V) as a function of the electrical charge (A.s) and welding rupture force (N x 100).

Based on these test results the selected welding parameters for the qualification test specimens manufacturing are the following:

a) Electrode force = 4 N;
b) Welding Voltage within the interval from 0.490 V to 0.580 V;
c) Voltage rising ramp time interval, t1 = 0.080 s;
d) Constant voltage time interval, t2 = 0.200 s;
e) Voltage drop ramp time interval, t3 = 0.10 s.
f) The monitored welding charge shall be within the interval from 40 A.s to 50 A.s.

The selected welding parameters were applied in 40 additional welding points for verification purposes, with the welding voltage set to 0.530 V. The results are shown in Fig. 4 now as a function of the welding average current, electrical charge and welding rupture force. All 40 welded points meets the minimum 1.5 N welding strength requirement.

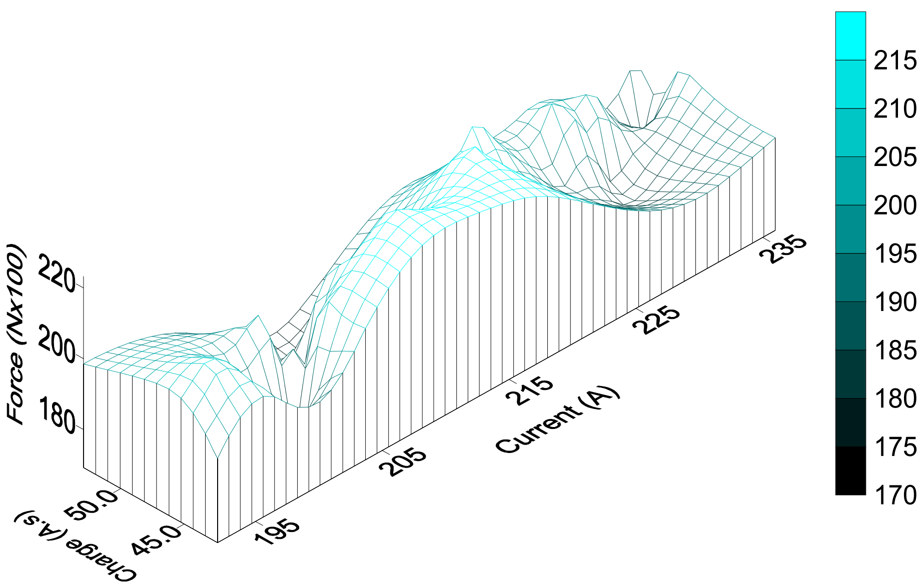

Figure 4: Selected welding parameters verification. Welding voltage set to 0.530 V.

5. Qualification Test Specimens

To demonstrate that the developed welding head equipment meets the product assurance requirements when submitted to a continuous operational condition, as would occur in a production for a large solar array, and also to demonstrate its operational repeatability and robustness, a set of qualification test specimens were manufactured in accordance to what was planned in an inspection and qualification test plan [Vaz, 2002].

In accordance with the established test plan, test specimens with the first two digits coded "T1" type are intended for verification of specific points in the solar array manufacturing process, being of special interest of the present work, the welding of the electrical interconnectors into the solar cells contacts. Test specimens with the first two digits coded coded "T2" type are intended to verify the quality of assembled parts or the quality of the solar array generator equipment as a whole.

The following types of qualification test specimens were manufactured for verifications related to the welding processes [Vaz, 2004-a]:

- T1-S1-CP1: they consist of a space solar cell (size 20 mm x 40 mm) with a 0.012 mm thick silver interconnector welded in its front side electrical contacts (8 welding points per test specimen);
- T1-S1-CP2: they are similar to the T1-S1-CP1 but with interconnectors welded in the front and back side contacts (16 welding points per test specimen);
- T2-M1-CP2: It consists of a solar module composed of 5 space applications solar cells (size 20 mm x 40 mm) serially interconnected (80 welding points);
- T2-M1-CP2: It consists of a solar module composed of 23 space applications solar cells (size 20 mm x 40 mm) serially interconnected (368 welding points);
- T2-T1-CP1: It consists of a small solar panel (test coupon) with two solar modules composed of 23 space solar cells (size 20 mm x 40 mm) serially interconnected (736 welding points);
- T2-P1-CP1: It consist of a full solar panel (1.0 m x 1.5 m), with 1610 space applications solar cells (size 20 mm x 40 mm), divided into 35 solar modules with 46 serial solar cells each (25760 welding points).

Table 1 shows the test matrix for the manufactured welding qualification test specimens. The crosses indicate the tests that each test specimen was submitted to. Visual inspection and electrical performance test were performed before and after the environmental [Vaz, 2002].

Table 1: Test Matrix showing the welding qualification tests specimens and the applied tests.

TEST/INSPECTION	WELDING QUALIFICATION TEST SPECIMEN						
	T1-S1-CP1	T1-S1-CP2	T1-C1-CP1	T2-M1-CP1	T2-M1-CP2	T2-T1-CP1	T2-P1-CP1
Thermal Shock						X	
Thermal Vacuum			X			X	X
Electrical Continuity						X	X
Electrical Performance			X	X	X	X	X
Pull Test	X	X		X	X		
Visual Inspection	X	X	X	X	X	X	X

6. Qualification Test Results

The qualification tests results are summarized in this section. The environmental tests, electrical performance tests and visual inspections were performed at the Laboratory of Integration and Test (LIT) of the Brazilian National Space Research Institute – (INPE). Figure 5 shows the T2-P1-CP1 test specimen being prepared for the thermal vacuum test at LIT/INPE [Almeida, 2004]. Pull tests were performed at the Orbital Engenharia.

Table 2 shows a representative sample of the pull test results performed in the T1-C1-CP1 and T1-C1-CP2 test specimen types [Vaz, 2004-b]. The requirement is welding rupture force higher than 1.5 N. As it can be observed from Table 2, most of the results meet the specified requirement. Among all results, three points were found non-conform, it means lower than 1.5 N, representing less than 3% of the total tested points. Due to the good results obtained in most of the welding points tested, the three points failure were associated to one of the following reasons: a) workmanship; b) non-conductive anti-reflecting coating over the solar cell contact; and c) surface contaminant in the welding area [Vaz, 2004-c].

Figure 5: T2-P1-CP1 Test Specimen being prepared for the thermal vacuum test at LIT/INPE.

Table 2: Welding rupture force (N) for the interconnector finger of the test specimens type T1-C1-CP1 and T1-C1-CP2 (representative sample).

Test Specimen Number	Interconnector Finger Position							
	1	2	3	4	5	6	7	8
028330	2.52	2.33	2.35	2.39	2.43	1.89	2.28	2.40
044815	2.70	2.19	1.69	2.09	2.19	1.57	2.09	2.41
020111	1.59	1.76	2.40	2.18	2.61	2.60	2.61	1.94
035202	2.32	2.26	2.35	1.62	2.31	2.20	2.46	2.03
035814	1.66	1.93	1.89	1.97	2.41	2.03	2.34	2.23
035925	1.47(1)	1.94	1.59	1.57	1.51	1.32	1.50	1.76

(1) Finger rupture without welding point rupture.

Figure 6 shows the typical appearance of the test specimen after the destructive pull test [Vaz, 2004-b]. It can be observed in Fig. 7 that part of the interconnector finger remains attached to the solar cell contact in the welding area.

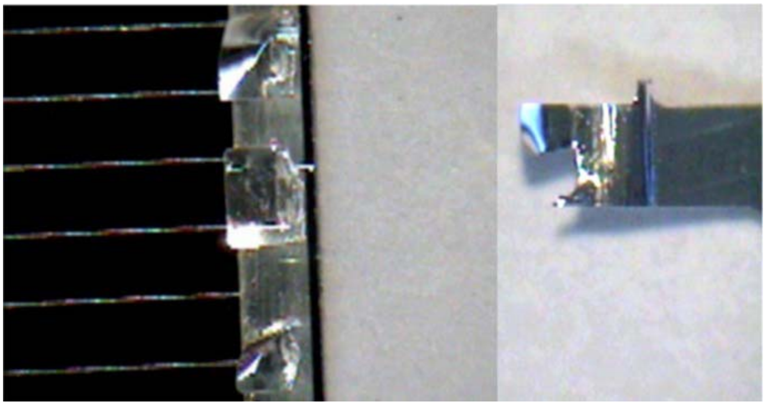

Figure 6: T1-S1-CP1 Test Specimen after destructive pull test. Part of the interconnectors fingers remains welded in the solar cell front contact (50x magnification).

The objective of the electrical performance test was to verify if the interconnector welding to the solar cell do not degrade the solar cell short circuit current more than 2%. Table 3 shows the electrical performance test results for the test specimens T1-C1-CP1 type, where “ΔIsc” is the percent variation of the solar cell short circuit current before and after interconnector welding. The results show that the interconnector welding meets the requirement described herein in item “2b” [Vaz, 2004-d]. Figure 7 shows the electrical performance test result in graphical format (voltage x current) for test specimen T1-S1-CP1-2 [Vaz, 2004-e].

Table 3: Tests specimens type T1-C1-CP1 electrical performance test before and after interconnector welding. ΔIsc is the percent variation in the solar cell short circuit current.

		Bare Solar Cell					Solar Cell with Interconnector Welded					
Test Specimen Id	Cell Id	Voc (V)	Vmp (V)	Isc (A)	Imp (A)	FF (%)	Voc (V)	Vmp (V)	Isc (A)	Imp (A)	FF (%)	ΔIsc (%)
T1-S1-CP1-1	029129	0.570	0.482	0.286	0.264	77.9	0.571	0.479	0.286	0.265	77.6	0
T1-S1-CP1-2	028220	0.598	0.511	0.294	0.267	77.4	0.597	0.503	0.293	0.270	77.4	-0.3
T1-S1-CP1-3	028139	0.598	0.492	0.297	0.276	76.3	0.596	0.490	0.297	0.272	75.1	0
T1-S1-CP1-4	028238	0.594	0.504	0.292	0.269	78.0	0.592	0.498	0.292	0.267	76.8	0
T1-S1-CP1-5	044826	0.575	0.487	0.291	0.269	78.1	0.574	0.482	0.291	0.269	77.5	0
T1-S1-CP1-6	044816	0.558	0.474	0.179	0.161	76.4	0.551	0.450	0.177	0.154	70.6	-0.7

Voc: open circuit voltage; Vmp: maximum power voltage; Isc: short circuit current; Imp: current at maximum power voltage; FF: fill factor.

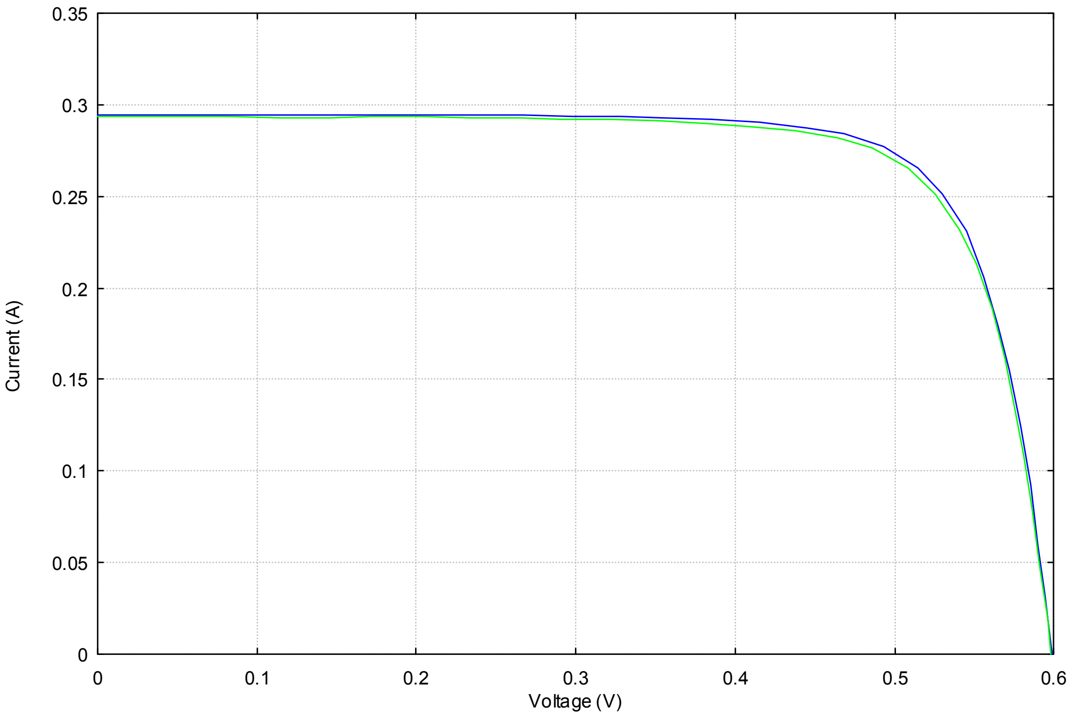

Figure 7: Typical electrical performance test result. Solar cell Current x Voltage characteristic before and after interconnector welding.

The electrical continuity test was performed in the test specimens T2-T1-CP1 (test coupon) and in the T2-P1-CP1 (solar panel) to verify the circuits electrical continuity before and after the environmental tests (thermal shock and thermal vacuum). The test specimens passed the electrical continuity tests without any non-conformance [Vaz, 2004-f].

The visual inspections were performed for all test specimens as indicated in Table 1. Non-conformances were found only for the T2-P1-CP1 Solar Panel test specimen after finishing its manufacturing, it means before the environmental test. It was reported in the visual inspection after manufacturing the following discrepancies that may be related to the welding process [Vaz, 2004-f]:

- Presence of hairline cracks in 9 solar cells (0.56% of the total number of welded cells);
- Presence of small corner crack in 1 solar cell (0.06% of the total number of welded cells).

The hairline crack is a micro scale crack type that sometimes appears nearby the welding areas due to the mechanical and thermal stresses induced by the welding process. Nevertheless, this type of defect does not have any impact on the solar panel mechanical nor electrical performances. In T2-P1-CP1 test specimen it was welded 1610 solar cells, it means that only 0.56% of the total welded cells presented this type of discrepancy. If this percent is taken in relation to the total number of the welding points it means 0.035% of the welded points.

After the environmental tests [Almeida, 2004-a, b and c] it was not reported any non-conformance related to the visual inspections for all test specimens [Vaz, 2004-c].

7. Conclusions

In this paper it was presented the development and qualification of a mechanical welding head intended for use in manufacturing solar arrays for space applications. The large amount of test specimens manufactured demonstrated the equipment repeatability and robustness and also its adequacy for the intended use. The qualification test results demonstrate the quality of the welding points executed using the developed equipment.

With the qualification test results obtained, the developed welding head was considered qualified by a qualification review board [Vaz, 2003-a] and it has been used to attend the solar array manufacturing demand for the satellites planned in the Brazilian Program for Space Activities - PNAE.

8. Acknowledgements

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9. References

AEB, Agência Espacial Brasileira. 1998. “PROGRAMA NACIONAL DE ATIVIDADES ESPACIAIS: 1998-2007”. 2. ed. – Brasília.

ALMEIDA, J. S.. 2004-a. “Relatório de Teste de Vácuo” – Laboratório de Integração e Testes - LIT (INPE/LIT.PS.005/03 OBT01-R01).

ALMEIDA, J. S.. 2004-b. “Relatório de Teste Termoclimáticos (Choque Térmico)” – Laboratório de Integração e Testes - LIT (INPE/LIT.PS.005/03 OBT01-R02).

ALMEIDA, J. S.. 2004-c. “Relatório de Teste de Ciclagem Vácuo-Térmica” – Laboratório de Integração e Testes - LIT (INPE/LIT.PS.005/03 OBT01-R03).

European Space agency (ESA). “Basic requirements for product assurance of ESA spacecraft and associated equipment. esa-pss-01-0”.

ILES, P.A.; Ho, F. F.. 1993. Space photovoltaics in the nineties. In: EUROPEAN SPACE POWER CONFERENCE, Graz. Proceedings. Graz, ESA, p. 729-732, (ESA WPP-054).

MIL-S-83576 Solar Cell Arrays, Space Vehicle, Design and Testing, General Spacification for.

VAZ, C. C.. 2002. Relatório Científico PIPE/FASE-I – Geradores Fotovoltaicos para Aplicações Aeroespaciais. FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2003-a. “Relatório Científico PIPE/FASE-II – Geradores Fotovoltaicos para Aplicações Aeroespaciais. FAPESP, Proc. 01/03041-2”.

VAZ, C. C.. 2003-b. “Determinação Experimental dos Parâmetros de Soldagem por “DC Resistance Welding” PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-RL-181). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-a. “Conteúdo do Pacote de Dados para a Revisão de Qualificação PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-PK-188). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-b. “Testes de Resistência Mecânica das Soldagens de Componentes de Geradores Fotovoltaicos (“Pull Test”) PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-RT-184). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-c. “Relatórios de Não Conformidade PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-PK-187). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-d. “Resultados dos Testes de Caracterização Elétrica (Simulador Solar Contínuo) PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-RT-182). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-e. “Resultados dos Testes de Caracterização Elétrica (Simulador Solar Pulsado “Flasher Test”) PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-RT-183). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-f. “Relatórios das Inspeções Visuais, Testes de Continuidade Elétrica, Isolamento Elétrico e Resistência do “Coverglass” ao Descolamento PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-RT-185). FAPESP, Proc. 01/03041-2.

VAZ, C. C.. 2004-g. “Síntese das Inspeções e Testes de Qualificação PIPE/FASE-II” – Geradores Fotovoltaicos para Aplicações Aeroespaciais (ORB-PIPE-2-100000-RL-186). FAPESP, Proc. 01/03041-2.

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