EVALUATION OF LASER WELDING TECHNIQUES
FOR HYDROGEN TRANSMISSION

MASTER

PROGRESS REPORT,

Period: 1 April 1978 - 30 April 1978

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19 May 1978

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Monthly Progress Report No. 7

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ABSTRACT

As the seventh progress report for this contract, the continuation of welded material mechanical properties tests are discussed.

19 May 1978

INTRODUCTION:

This report is submitted in accordance with the requirements of Department of Energy (ERDA) Contract EC-77-C-02-4355, and represents the seventh monthly letter progress report covering the period 1 April 1978 to 30 April 1978. This contract which was initiated on 30 September 1977 is sponsored by Dr. James H. Swisher, Assistance Director, Physical Storage Systems, Washington D.C. under the technical cognizance of Dr. Howard G. Nelson, NASA-Ames Research Center, Moffitt Field, California. This report is divided into sections summarizing the technical aspects of the program including work performed to start of reporting period and work performed during reporting period, including test results and technical problems.

WORK PERFORMED BY START OF REPORTING PERIOD:

Metallurgical evaluation to characterize the gas-tungsten arc (GTA) and electron beam (EB) weld joints for both the AISI 304L and ASTM A106B materials had been completed and fractographic analyses of test specimens was continuing.

Tensile testing of the A106B GTA welded specimens and low-cycle fatigue testing of the AISI 304L GTA and EB welded specimens had been completed. Fracture toughness testing of the A106B GTA welded material was in progress.

Laser welding of both the AISI 304L and A106B materials was continuing.

WORK PERFORMED DURING THE REPORTING PERIOD:Material Preparation and Weld Evaluation

Machining of the A106B GTA and EB welded specimens has been completed.

Laser welding of the AISI 304L and A106B materials is continuing at the United Technologies Research Center. It is anticipated that the laser welding will be completed by 31 May 1978. Test specimen machining and subsequent testing will be initiated upon receipt of the material.

Chromatographic analysis of the subject materials was conducted in an effort to explain the numerous egg-shaped pores observed in the fracture surfaces of most of the welded specimens. The oxygen content of the AISI 304L and A106B was determined to be 94 and 45 ppm, respectively. These high pre-weld oxygen levels are considered typical for these steels and, in part, explains the frequent occurrence of the pores in the fracture surfaces.

Tensile Testing

Tensile testing of the A106B EB welded specimens was initiated and completed. All tensile test results generated to date are listed in Table I.

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Tensile Testing (Continued)

Testing of the Al06B EB welded material indicated generally lower ductility than the parent material. Average reduction in elongation and reduction of area of approximately 19 and 30% respectively, was exhibited due to the 13.8 MPa (2000 psig) hydrogen environment. Notch tensile tests of the EB welded material indicated approximately 12 and 21% average degradation in strength for the fusion and heat affected zone specimens respectively, due to the hydrogen environment.

All tensile test requirements in this program have now been completed with the exception of the laser welded material.

Low-Cycle Fatigue

Low-cycle fatigue (LCF) testing of the Al06B welded material has been completed. All LCF test data generated to date are listed in Table II and presented graphically in Figure 1.

LCF testing of the Al06B material in 13.8 MPa (2000 psig) hydrogen indicates reductions in mean life of approximately 50 and 27% due to the GTA and EB welding respectively.

The aforementioned conclusion, and previous ones made for the AISI 304L material, must be qualified in view of the condition of the welded specimens and the data scatter experienced. Welded LCF specimen fracture surfaces showed virtually all failures originating from pores and voids ranging from pin-point size to approximately 1.5 mm (0.06 in) in diameter. This extent of porosity is typical for these materials and is within the maximum permissible range per ASME Boiler and Pressure Vessel Code standards. In view of this, firm conclusions as to the effect of various welds on the LCF life of the subject materials cannot be made. Moreover, additional testing (outside the scope of this program) may even alter those conclusions already made.

All LCF testing has been completed with the exception of the laser welded material.

Fracture Toughness Testing

Fracture toughness testing of the Al06B GTA and EB welded materials was completed, with data analysis currently in progress. All fracture toughness test data generated to date are listed in Table III.

As for the tensile and LCF testing in this program, all fracture toughness testing has been completed with the exception of the laser welded material.

TECHNICAL PROBLEMS:

No technical problems were encountered during this reporting period.

TABLE I

TENSILE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH PRESSURE GASEOUS HYDROGEN ENVIRONMENT AT 24°C (75°F)

MATERIAL	WELD TYPE	SPEC. S/N	TEST CONDITIONS		TEST RESULTS					
			NOTCH FACTOR	ENVIRON- MENT ⁽¹⁾	S T R E N G T H				D U C T I L I T Y	
					0.2% YIELD		U L T I M A T E		EL ⁽²⁾	RA
					MPa	ksi	MPa	ksi	%	%
AISI 304L	Parent Mat'l	SPMS-1	Smooth	Air	215.8	31.3	598.5	86.8	64.0	83.2
		SPMS-2	Smooth	Air	226.8	32.9	592.3	85.9	61.0	83.1
		SPMS-3	Smooth	H ₂	245.5	35.6	622.6	90.3	66.3	81.1
		SPMS-4	Smooth	H ₂	245.5	35.6	626.7	90.9	68.0	81.1
		SPMN-1	8.0	Air			801.2	116.2		
		SPMN-2	8.0	Air			814.3	118.1		
		SPMN-3	8.0	H ₂			771.5	111.9		
		SPMN-4	8.0	H ₂			762.6	110.6		
	GTA	SGFS-1	Smooth	Air	300.6	43.6	613.6	89.0	35.0	27.5 ⁽³⁾
		SGFS-2	Smooth	Air	299.9	43.5	564.7	81.9	25.5	30.4 ⁽³⁾
		SGFS-3	Smooth	H ₂	291.6	42.3	619.1	89.8	52.0	72.4 ⁽⁴⁾
		SGFS-4	Smooth	H ₂	316.5	45.9	663.3	96.2	61.0	75.2 ⁽⁴⁾
		SGFN-1	8.0	Air			846.7	122.8		
		SGFN-2	8.0	Air			843.9	122.4		
		SGFN-3	8.0	H ₂			817.7	118.6		
		SGFN-4	8.0	H ₂			829.4	120.3		
	GTA(HAZ)	SGHN-1	8.0	Air			922.5	133.8		
		SGHN-2	8.0	Air			861.2	124.9		
		SGHN-3	8.0	H ₂			870.8	126.3		
		SGHN-4	8.0	H ₂			872.2	126.5		
	EB	SEFS-1	Smooth	Air	268.2	38.9	580.5	84.2	40.0	77.5 ⁽⁵⁾
		SEFS-2	Smooth	Air	280.6	40.7	584.0	84.7	42.0	84.2 ⁽⁵⁾
		SEFS-3	Smooth	H ₂	289.6	42.0	607.4	88.1	40.0	69.6 ⁽⁵⁾
		SEFS-4	Smooth	H ₂	296.5	43.0	606.0	87.9	40.5	71.2 ⁽⁵⁾

TABLE I (Cont'd)

TENSILE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH PRESSURE GASEOUS HYDROGEN ENVIRONMENT AT 24°C (75°F)

MATERIAL	WELD TYPE	SPEC. S/N	TEST CONDITIONS		TEST RESULTS					
			NOTCH FACTOR	ENVIRON- MENT ⁽¹⁾	S T R E N G T H				D U C T I L I T Y	
					0.2% YIELD		U L T I M A T E		EL ⁽²⁾ %	RA %
					MPa	ksi	MPa	ksi		
AISI 304L	EB	SEFN-1	8.0	Air			834.3	121.0		
		SEFN-2	8.0	Air			848.1	123.0		
		SEFN-3	8.0	H ₂			831.5	120.6		
		SEFN-4	8.0	H ₂			795.7	115.4		
	EB(HAZ)	SEHN-1	8.0	Air			820.5	119.0		
		SEHN-2	8.0	Air			861.2	124.9		
		SEHN-3	8.0	H ₂			813.6	118.0		
		SEHN-4	8.0	H ₂			799.8	116.0		
	Parent Mat'l	CPMS-1	Smooth	Air	323.4	46.9	479.2	69.5	28.5	60.5
		CPMS-2	Smooth	Air	333.0	48.3	492.3	71.4	27.3	60.6
		CPMS-3	Smooth	H ₂	349.6	50.7	513.0	74.4	24.0	40.5
		CPMS-4	Smooth	H ₂	341.3	49.5	509.5	73.9	24.5	45.2
		CPMN-1	8.0	Air			798.4	115.8		
		CPMN-2	8.0	Air			791.5	114.8		
		CPMN-3	8.0	H ₂			695.7	100.9		
		CPMN-4	8.0	H ₂			681.2	98.8		
		CGFS-1	Smooth	Air	308.2	44.7	504.7	73.2	21.0	59.9 ⁽⁴⁾
		CGFS-2	Smooth	Air	311.6	45.2	507.5	73.6	21.0	59.6 ⁽⁴⁾
		CGFS-3	Smooth	H ₂	311.6	45.2	501.2	72.7	17.5	57.4 ⁽⁴⁾
		CGFS-4	Smooth	H ₂	319.9	46.4	502.6	72.9	17.0	47.0 ⁽⁴⁾
A106B	GTA	CGFN-2	8.0	Air			1025.9	148.8		
		CGFN-6	8.0	Air			1012.8	146.9		
		CGFN-3	8.0	H ₂			904.6	131.2		
		CGFN-4	8.0	H ₂			910.8	132.1		

TABLE I (Cont'd)

TENSILE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH PRESSURE GASEOUS HYDROGEN ENVIRONMENT AT 24°C (75°F)

MATERIAL	WELD TYPE	SPEC. S/N	TEST CONDITIONS		TEST RESULTS				DUCTILITY	
			NOTCH FACTOR	ENVIRON- MENT ⁽¹⁾	S T R E N G T H				EL ⁽²⁾ %	RA %
					0.2% YIELD		ULTIMATE			
					MPa	ksi	MPa	ksi		
A106B	GTA (HAZ)	CGHN-1	8.0	Air			848.1	123.0		
		CGHN-2	8.0	Air			843.2	122.3		
		CGHN-3	8.0	H ₂			639.8	92.8		
		CGHN-4	8.0	H ₂			665.3	96.5		
	EB	CEFS-1	Smooth	Air	313.7	45.5	498.5	72.3	24.0	59.4 ⁽⁴⁾
		CEFS-2	Smooth	Air	319.2	46.3	500.6	72.6	24.0	59.2 ⁽⁴⁾
		CEFS-3	Smooth	H ₂	317.8	46.1	494.4	71.7	19.0	37.8 ⁽⁴⁾
		CEFS-4	Smooth	H ₂	315.8	45.8	494.4	71.7	20.0	45.0 ⁽⁴⁾
		CEFN-1	8.0	Air			804.6	116.7		
		CEFN-2	8.0	Air			824.6	119.6		
		CEFN-3	8.0	H ₂			710.2	103.0		
		CEFN-4	8.0	H ₂			758.4	110.0		
		CEFN-5	8.0	H ₂			684.6	99.3		
	EB (HAZ)	CEHN-1	8.0	Air			804.6	116.7		
		CEHN-2	8.0	Air			810.8	117.6		
		CEHN-3	8.0	H ₂			644.7	93.5		
		CEHN-4	8.0	H ₂			628.1	91.1		

(1) Air tests at 1 atmosphere, hydrogen tests at 13.8 MPa (2000 psig)

(2) Elongation based on gage length of 25.4 mm (1.00 inch) or 4D.

(3) Failed in weld HAZ.

(4) Failed in parent material.

(5) Failed in weld.

TABLE II

LOW CYCLE FATIGUE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH PRESSURE HYDROGEN ENVIRONMENT AT 24°C (75°F).

TEST CONDITIONS					TEST RESULTS			
MATERIAL	WELD TYPE	SPEC. S/N	ENVIRONMENT (1)	TOTAL STRAIN RANGE (2)	CYCLES TO FAILURE	INELASTIC STRAIN RANGE, %		
				%		MIN.	MAX.	AVE.
AISI 304L	Parent Material	SPML-1	Air	1.0	4,511	0.64	0.68	0.66
		SPML-2	Air	1.0	5,943	0.65	0.67	0.66
		SPML-6	Air	1.0	5,437	0.63	0.69	0.66
		SPML-3	Hydrogen	1.0	2,285	0.58	0.65	0.62
		SPML-4	Hydrogen	1.0	1,882	0.58	0.69	0.64
	GTA	SGFL-5	Air	1.0	4,113	0.53	0.62	0.58
		SGFL-1	Hydrogen	1.0	620	0.54	0.59	0.57
		SGFL-2	Hydrogen	1.0	1,054	0.50	0.62	0.56
		SGFL-4	Hydrogen	1.0	915	0.55	0.60	0.58
	EB	SEFL-1	Hydrogen	1.0	647	0.53	0.59	0.56
		SEFL-2	Hydrogen	1.0	617	0.56	0.58	0.57
		SEFL-6	Hydrogen	1.0	1,204	0.56	0.63	0.60
		SEFL-7	Hydrogen	1.0	920	0.57	0.63	0.60
		SEFL-8	Hydrogen	1.0	745	0.50	0.60	0.55
		SEFL-9	Hydrogen	1.0	1,259	0.52	0.60	0.56
A106B	Parent Material	CPML-1	Air	1.0	4,555	0.67	0.77	0.72
		CPML-2	Air	1.0	4,171	0.64	0.67	0.66
		CPML-5	Air	1.0	4,027	0.65	0.69	0.67
		CPML-4	Hydrogen	1.0	283	0.54	0.62	0.58
		CPML-6	Hydrogen	1.0	1,165	0.64	0.68	0.66
		CPML-7	Hydrogen	1.0	550	0.61	0.67	0.64
		CPML-8	Hydrogen	1.0	315	0.61	0.69	0.65
		GTA	CGFL-1	Hydrogen	1.0	669	0.31	0.50
	CGFL-2		Hydrogen	1.0	180	0.32	0.54	0.43
	CGFL-3		Hydrogen	1.0	195	0.43	0.51	0.47
	CGFL-4		Hydrogen	1.0	152	0.42	0.51	0.47

TABLE II (Continued)

LOW CYCLE FATIGUE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH PRESSURE HYDROGEN ENVIRONMENT AT 24°C (75°F)

<u>TEST CONDITIONS</u>					<u>TEST RESULTS</u>			
<u>MATERIAL</u>	<u>WELD TYPE</u>	<u>SPEC. S/N</u>	<u>ENVIRONMENT</u> (1)	<u>TOTAL STRAIN RANGE</u> (2) %	<u>CYCLES TO FAILURE</u>	<u>INELASTIC STRAIN RANGE, %</u>		
						<u>MIN.</u>	<u>MAX.</u>	<u>AVE.</u>
A106B	EB	CEFL-1	Hydrogen	1.0	171	0.57	0.63	0.60
		CEFL-2	Hydrogen	1.0	920	0.56	0.62	0.59
		CEFL-3	Hydrogen	1.0	386	0.53	0.53	0.53
		CEFL-4	Hydrogen	1.0	272	0.59	0.65	0.62

(1) Air tests at 1 atmosphere, hydrogen tests at 13.8 MPa (2000 psig).

(2) Mean Strain = 0, cyclic frequency = 5 cycles/min.

TABLE III

FRACTURE TOUGHNESS OF AISI 304L AND A106B IN AIR AT 24°C (75°F)

SPECIMEN PARAMETERS				TEST RESULTS							
MATERIAL	WELD TYPE	SPEC. S/N	PRECRACK LENGTH, a		$K_Q^{(1)}$ (MPa√m)	$K_Q^{(1)}$ (ksi√in)	$2.5 (K_Q/ys)^{2(2)}$	P_{max}/P_Q	$R_{SG}^{(3)}$	$K_{IC}(J)^{(4)}$	
			(mm)	(in)						MPa√m	ksi√in
AISI 304L	Parent Mat'l	SPMF-1	14.2	.560	47.1	42.9	4.77	2.03	6.16		
		SPMF-2	15.8	.622	44.4	40.4	3.96	2.17	6.55		
	GTA	SGFF-1	14.1	.556	56.5	51.5	6.43	1.49	5.41		
		SGFF-2	15.8	.621	58.0	52.8	6.76	1.42	5.77		
	GTA(HAZ)	SGHF-1	13.5	.531	59.4	54.1	7.11	1.67	6.13		
		SGHF-2	15.7	.618	49.0	44.6	4.83	1.80	6.15		
	EB	SEFF-1	13.6	.536	56.1	51.1	6.31	1.72	6.01		
		SEFF-2	16.0	.629	46.8	42.6	4.40	1.90	6.32		
	EB(HAZ)	SEHF-1	17.0	.670	50.8	46.2	5.18	1.79	6.86		
		SEHF-2	13.4	.529	55.7	50.7	6.23	1.71	5.84		
A106B	Parent Mat'l	CPMF-1	13.0	.513	49.8	45.3	2.26	1.48	2.99	195.1	177.5
		CPMF-2	15.1	.595	51.4	46.8	2.42	1.32	3.09		

(1) (2) These parameters are included for informational purposes only, as per ASTM E399-74 with P_{max}/P_Q greater than 1.10, K_Q bears no relation whatsoever to K_{IC} .

(3) Specimen Strength Ratio - total stress (Mc/I + P/A)/yield strength.

(4) K_{IC} obtained using J-Integral method per Begley, J.A. and Landes, J.D., "The J-Integral As a Fracture Criterion," ASTM STP 514, 1972, and Bucci, R.J., Paris, P.C. et. al., "J-Integral Estimation Procedures," ASTM 514, 1972.