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TRW

Interoffice Correspondence

Civilian Radioactive Waste Management System
Management & Operating Contractor

TRW Environmental
Safety Systems Inc.

QA: QA

Subject Documentation of Literature on Residual Stress Measurements	**Date** May 19, 2000 LV.WP.VP.05/00-070	**From** Venkataramaran Pasupathi
To G. M. Gordon	**cc w/encl:** Gopal De File RPC = 1 Page	**Location/Phone** SUM1/423-1028B (702) 295-4507

The purpose of this correspondence is to capture in the Project's record system, the enclosed literature on residual stress measurements from the Plasma Fusion Center of Massachusettes Institute of Technology. It is expected that the data will be used as non-Q information to support the waste package PMR and the SCC AMR ICN 1.

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MEMORANDUM

To: Dr. Neil Mitchell, JCT
Dr. Frank Wong, JCT
Dr. E. Salpietro, EUHT
Dr. H. Tsuji, JAHT
Dr. O.Filatov, RHT

From: Robert N. Randall

Date: October 21, 1996

Ref.#: ITER/US/96/EV-MAG/R.N.RANDALL/Oct 21/-1

Attached is a CORRECTED COPY of the compilation of the residual stress measurements made by Lambda Research, Inc. on samples of Incoloy 908 tubing furnished by MIT and Inco Alloys International. Inadvertently an incomplete copy was sent to you last week. To avoid confusion please discard the earlier copy.

cc R. Ballinger
R. Jayakumar
J.V. Minervini
B. Smith

TO: G. GORDON
FROM: F. WONG
FAX: 5-4438

20 PAGES

ABSTRACT

In order to construct the ITER Model Coil safely it was necessary to insure that no SAGBO caused cracking would occur in the Incoloy 908 conduits. To determine the extent of the hazard and the effect of preventative measures a variety of samples were sent to Lambda Research, Inc. in Cincinnati, Ohio for measurement of the residual surface stresses. Depending on the processing in the fabrication of the samples stresses were found that could be risky to have in the actual conduit. Shot peening of the surface was found to produce a safe compressive surface stress.

INTRODUCTION

Incoloy 908 is an alloy that was developed jointly by Inco Alloys International, Inc and MIT to use a conduit for composite Nb_3Sn superconducting cables in CIC, (Cable In Conduit), type conductors. The alloy was tailored to have a coefficient of thermal expansion that closely matched the CTE of composite Nb_3Sn conductors so that thermal stresses induced during cooldown would be limited and stress induced degradtion of the Nb_3Sn current density would be minimized.

The sensitivity of the alloy to cracking due to SAGBO, (stress assisted grain boundary oxidation), and the catastrophic failure that might result was the catalyst for this testing program. Unfortunately, SAGBO occurs in the range of temperatures in which a conductor is given the diffusion heat treatment to form the Nb_3Sn. In addition to the temperature requirement, there must be a minimum stress level and a minimum amount of oxygen in the system for cracking to occur.

This program was devised to determine the stresses found in manufactured conduits and the effect of measures to reduce the stresses to safe levels.

TEST PROGRAM

Part of the testing was requested by IAII and part by MIT. All results are included. One difference beween the tests of these samples is that the transverse stress was measured in the IAII samples, and the longitudinal stresses were measured in the MIT samples. The list of samples and test locations are shown in Tables IX and X.

The text procedure descibed in the following pages is excerpted from Lambda Research reports.

TECHNIQUE

X-ray diffraction residual stress measurements were made at the surface and at a nominal depth of 0.5 mm. Measurements were made in the longitudinal direction at the mid-length and mid-width on the outside surface and at a similar location on the inside surface 90 deg. away.

Sectioning was necessary prior to the inside surface x-ray diffraction residual stress measurements in order to provide access for the incident and diffracted x-ray beams. The outside measurements were made before sectioning the tube. Prior to sectioning, a single electrical resistance strain gage rosette was applied at the inside measurement location. The total strain relaxation which occurred as a result of sectioning was recorded after the sectioning process was complete.

The sample was rocked through an angular range of ±1.0 deg. around the mean psi angles during measurement to integrate the diffracted intensity over more grains, minimizing the influence of the grain size.

X-ray diffraction residual stress measurements were performed using a two-angle sine-squared-psi technique, in accordance with GE specification 4013195-991 and SAE J784a, employing the diffraction of manganese K-alpha radiation from the (311) planes of the FCC structure of the Incoloy 908. The diffraction peak angular positions at each of the psi tilts employed for measurement were determined from the position of the K-alpha 1 diffraction peak separated from the superimposed K-alpha doublet assuming a Pearson VII function diffraction peak profile in the high back-reflection region.[1] The diffracted intensity, peak breadth, and position of the K-alpha 1 diffraction peak were determined by fitting the Pearson VII function peak profile by least squares regression after correction for the Lorentz polarization and absorption effects and for a linearly sloping background intensity.

Details of the diffractometer fixturing are outlined below:

Incident Beam Divergence:	1.0 deg.
Detector:	Si(Li) set for 90% acceptance of the manganese K-alpha energy
Psi Rotation:	10 to 50 deg.
Irradiated Area:	5 mm x 2 mm (long axis in the direction of measurement) 5.0 mm x 4.0 mm for all inside diameter locations and the outside diameter locations on Specimens TF2 Compacted Xverse Weld #1 and TF2 C38 Tube Bent and Straightened 5.0 mm x 5.0 mm for all other outside diameter locations 5.0 mm x 0.5 mm for the corner locations.

The value of the x-ray elastic constant, $E/(1 + \nu)$, required to calculate the macroscopic residual stress from the strain measured normal to the (311) planes of Incoloy 908 was previously determined empirically [2] employing a simple rectangular beam manufactured from Incoloy 908

loaded in four-point bending on the diffractometer to known stress levels and measuring the resulting change in the spacing of the (311) planes in accordance with ASTM E1426-91.

For the measurements performed during this investigation, it was not possible to correct the results for the effects of penetration of the radiation employed for residual stress measurement into the subsurface stress gradient. A surface and two subsurface measurements are needed to make the corrections. The magnitude of the gradient correction can be quite significant, particularly on machined or ground surfaces, and can even change the sign of surface results.

Material was removed electrolytically for subsurface measurement, minimizing possible alteration of the subsurface residual stress distribution as a result of material removal.

The (311) diffraction peak width was calculated simultaneously with the macroscopic residual stress. The (311) diffraction peak width is a sensitive function of the chemistry, hardness, and the degree to which the material has been cold worked. In martensitic steels, it is commonly observed that plastic deformation produced by processes such as shot peening or grinding will cause work softening, and a reduction in the peak width. In work hardening materials, the diffraction peak width increases significantly as a result of an increase in the average microstrain and the reduced crystallite size produced by cold working. The (311) diffraction peak width can be indicative of how the material may have been processed, and the depth to which it has been plastically deformed.

The strain relaxations were recorded as a result of sectioning each tube for residual stress measurement on the inside surface. These strains were combined employing Mohr's Circle for Strain to calculate the maximum and minimum normal principal residual stress relaxations, the maximum shear stress, and the orientation of the maximum normal residual stress relaxation direction defined by the angle phi. Phi is taken to be a positive angle counterclockwise from the no. 1 reference direction. The residual stress relaxations resolved in directions of strain measurement were then calculated from the principal residual stress relaxations. The stress relaxations in the longitudinal direction were between +138 MPa and -138 MPa. The wide variation in the stress relaxation is probably a result of varying processing parameters in the eleven tubes examined.

The error shown for each residual stress measurement is one standard deviation resulting from random error in the determination of the diffraction peak angular positions and in the empirically determined value of $E/(1+\nu)$ in the <311> direction. An additional semi-systematic error on the order of ± 2 ksi (± 14 MPa) may result from sample positioning and instrument alignment errors. The magnitude of this systematic error was monitored using a powdered metal zero-stress standard in accordance with ASTM specification E915, and found to be +11 MPa ksi during the course of this investigation.

REFERENCES:

(1) P.S. Prevey, *Adv. in X-Ray Anal.*, Vol. 29, 1986, pp. 103-111.

(2) P.S. Prevey, *Adv. in X-Ray Anal.*, Vol. 20, 1977, pp. 345-354.

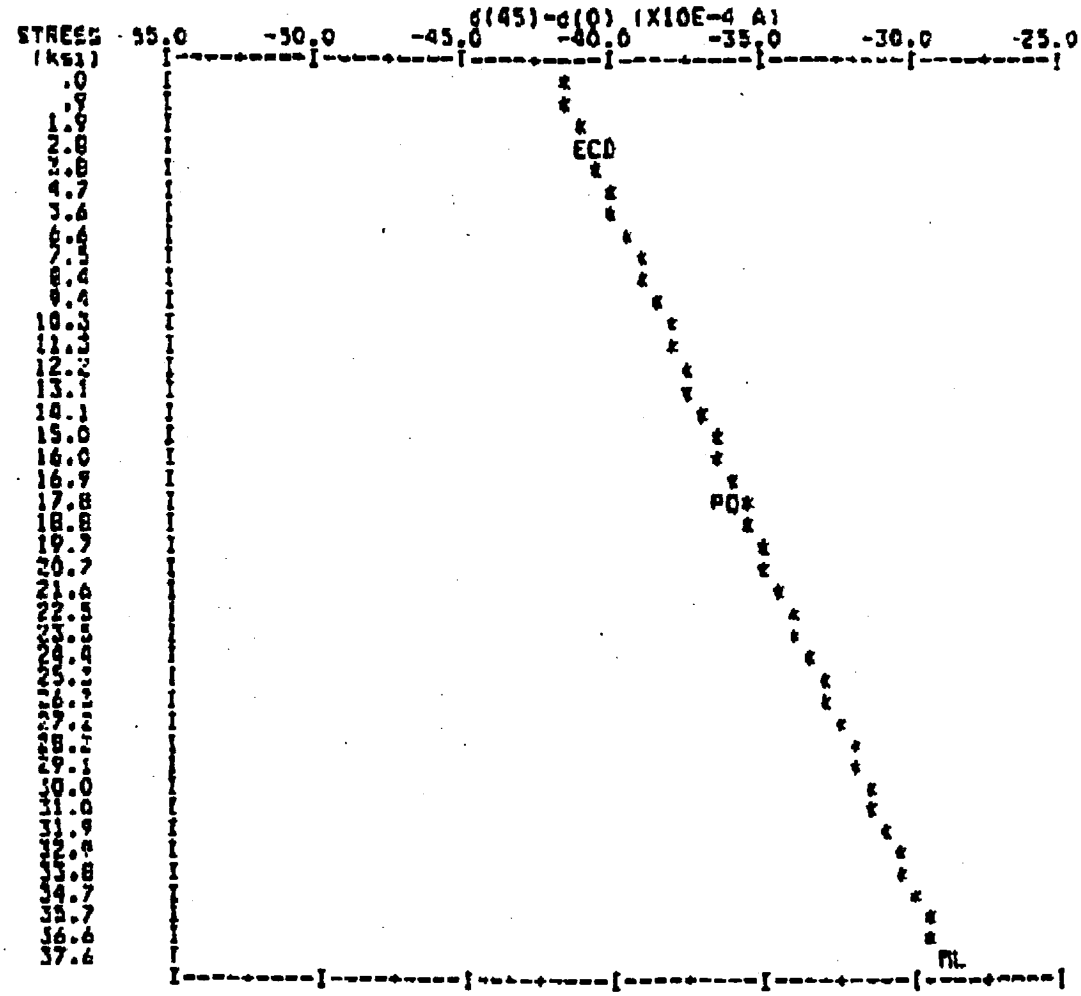
Lambda Research, Inc.

6001.c13	CAL183.11	10/05/95

E/(1+γ) DETERMINATION

GD 5/19/00

6001.d13	Incoloy 908 (311)	9510803TL



PSI= 30.0 (deg.) DO= 1.088002 (A) E/(1+V)= 19032. +- 364. (ksi)

Lambda Research

6001.c13 Lambda Research, Inc. 10/03/95

CALIB3.11

E/(1+V) DETERMINATION

6001.d13 Incoloy 908 (311) GD 5/13/00 9510003TL

	2TH 0	2TH PSI	D 0	D PSI	DEL 2TH	DEL D	STRESS
A	149.892	151.549	1.088256	1.084155	1.656	-.004101	2.57
B	149.885	151.531	1.088276	1.084198	1.646	-.004078	2.56
C	149.895	151.546	1.088251	1.084161	1.652	-.004090	2.55
D	149.905	151.533	1.088223	1.084192	1.628	-.004032	2.55
E	149.886	151.552	1.088272	1.084147	1.666	-.004125	2.55
F	150.001	151.465	1.087980	1.084355	1.465	-.003625	17.49
G	149.973	151.453	1.088051	1.084386	1.480	-.003665	17.50
H	149.991	151.470	1.088005	1.084345	1.477	-.003660	17.50
I	150.095	151.280	1.087741	1.084803	1.185	-.002938	37.55
J	150.101	151.286	1.087725	1.084789	1.185	-.002936	37.55
K	150.104	151.271	1.087719	1.084825	1.167	-.002894	37.55
L	150.110	151.278	1.087704	1.084808	1.168	-.002896	37.55
M	150.102	151.280	1.087722	1.084804	1.177	-.002919	37.55
N	149.989	151.448	1.088010	1.084397	1.459	-.003613	17.56
O	149.974	151.434	1.088049	1.084431	1.461	-.003619	17.56
P	149.976	151.453	1.088042	1.084384	1.477	-.003658	17.56

Slope= 29808.7 +- 570.8 (ksi/A) Lambda= 2.101820 (A) Psi= 50.0 (deg)

Do= 1.088007 (A) E/(1+v)= 19032. +- 364. (ksi) (+- 1.9%)

Lambda Research

6114.n01 | Lambda Research, Inc. PSTRAIN.12 | 10/17/95

CALCULATION OF PRINCIPAL AND RESOLVED STRESSES FOR REC. ROSETTES 1

MODULUS OF ELASTICITY = 25.4 (X10^6 PSI) POISSON RATIO - .263

6114 Incoloy 200 mm tube I.D. Loc. 1=Circ

MEASURED STRAINS: E1= 1956. E2= 762. E3= -126. (X10-6)

DIRECTION	RESOLVED STRESS (KSI)	PHI (DEG)
1	52.5	-175.8
2	28.5	-130.8
3	10.7	-85.8

MAX STRESS= 57.7 (KSI)
MIN STRESS= 10.5 (KSI)
MAX SHEAR STRESS= +- 21.1 (KSI)
PHI= 178.0 (DEG)

Lambda Research

SAMPLES TESTED FROM MIT

These samples were sent for measurement of residual longitudinal surface and in some cases, subsurface, (0.25 to 0.5mm), residual stresses. While the measurement of residual stress was done only on the outside on some samples, on others the residual stresses were also measured on the id of the conduits. The CS tubes were made by extrusion. Subsequently the initial procedure was to machine them to size. This was found unsatisfactory and in the final production process the extruded tubes were drawn to the final size. The TF tubes were made by rolling and welding followed by drawing to the final size. The US/DPC tubing was also rolled and welded and then turksheaded to final size.

The first tests were done on a sample of the US/DPC tubing as the conduit for the US/DPC was successfully manufactured, formed into a coil, heat treated and tested with no evidence of SAGBO cracking. A sketch of the US/DPC tubing is shown below and the measurement results are shown in Table I.

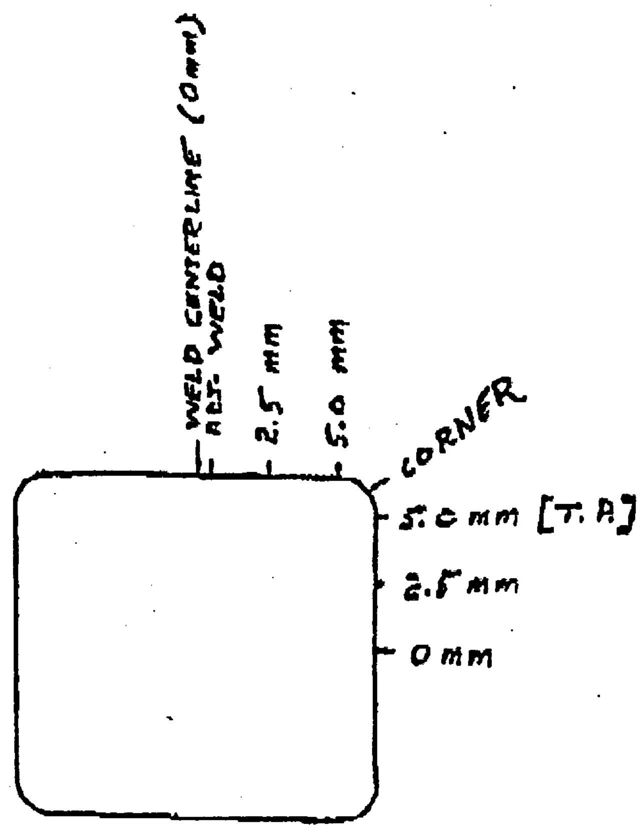


Figure 1: Incoloy 908 US-DPC Specimen

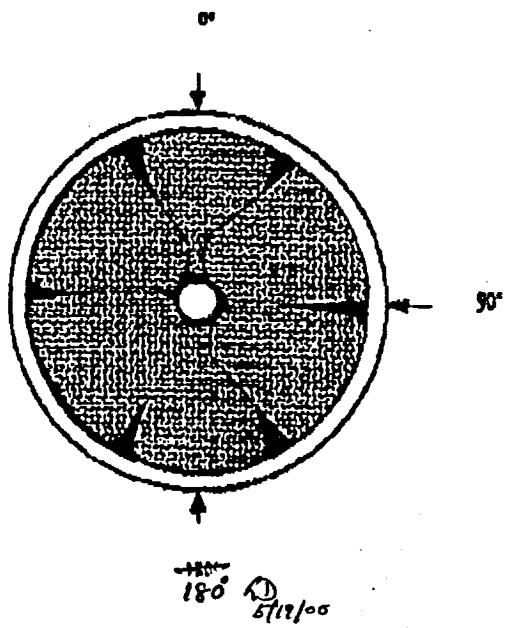
TABLE I
US/DPC SAMPLE

LONGITUDINAL RESIDUAL STRESSES
Mid Length Locations

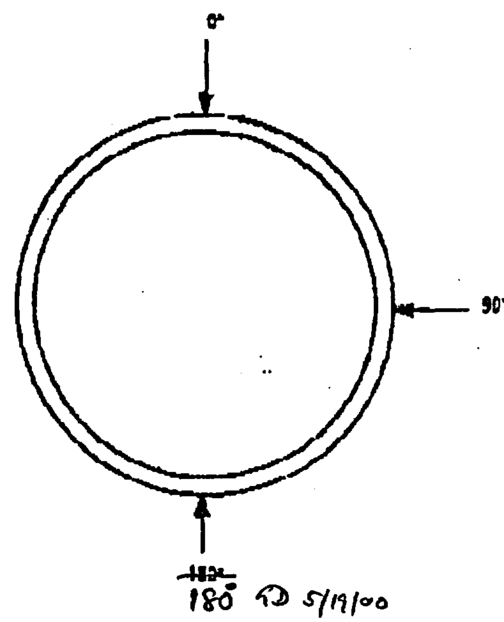
Specimen	Location	Residual Stresses (MPa) Surface	Residual Stresses (MPa) Sub Surface	Peak Width (deg) Surface	Peak Width (deg) Sub Surface
US/DPC SAMPLE					
	Weld Line	+205 ± 12	--	2.79	--
		+245 ± 12**	--	2.84	--
		± 6% +188 ± 12**	--	2.81	--
		+ 20% +327 + 67***	--	3.09	--
	Adj. weld line	+481 ± 19	--	3.65	--
	2.5mm from weld	+192 ± 14	--	3.51	--
	5.0mm from weld	+363 ± 16	--	3.07	--
	Corner	+158 ± 11	--	2.75	--
	5.0mm (side)	-93 ± 10	--	2.84	--
	2.5mm (side)	+192 ± 14	--	3.51	--
	0.0mm (side)	+102 ± 11	--	2.98	--
		+127 ± 10***	--	2.73	--

** Repeat 2 angle measurement
*** Multi angle Sine^2(psi) technique

Because the PTF sample would be the first ITER size conductor to be processed samples of the round PTF tubes were tested, both as compacted and as compacted and shot peened.



PTF Sample As Compacted



Compacted & Shot Peened

TABLE II
PTF SAMPLE

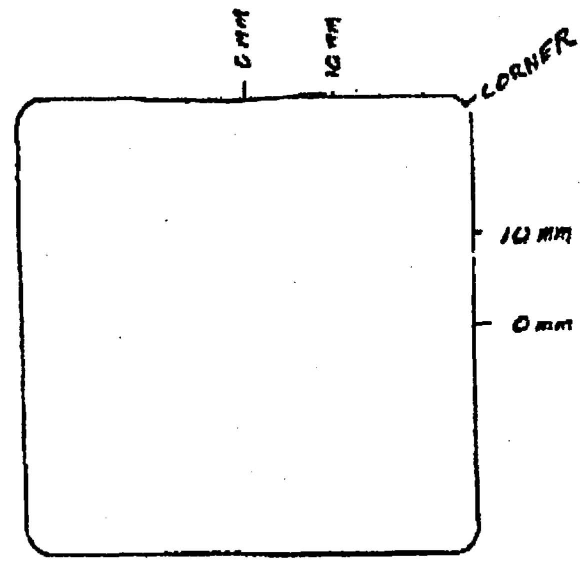
LONGITUDINAL RESIDUAL STRESSES
Mid Length Locations

Specimen	Location	Residual Stresses (MPa) Surface	Residual Stresses (MPa) Sub Surface (0.5mm)	Peak Width (deg) Surface	Peak Width (deg) Sub Surface (0.5mm)
PTF SAMPLE					
As Compacted	0 deg	+644 ± 21	+556 ± 16	2.81	1.54
	90 deg	+793 ± 23	+481 ± 14	2.54	1.45
	180 deg	+535 ± 18	+538 ± 15	2.53	1.55
Compacted & Shot Peened	0 deg	-891 ± 30	+420 ± 13	3.93	1.33
	90 deg	-892 ± 29	+408 ± 12	3.73	1.31
	180 deg	832 ± 28	+418 ± 28	4.09	1.45

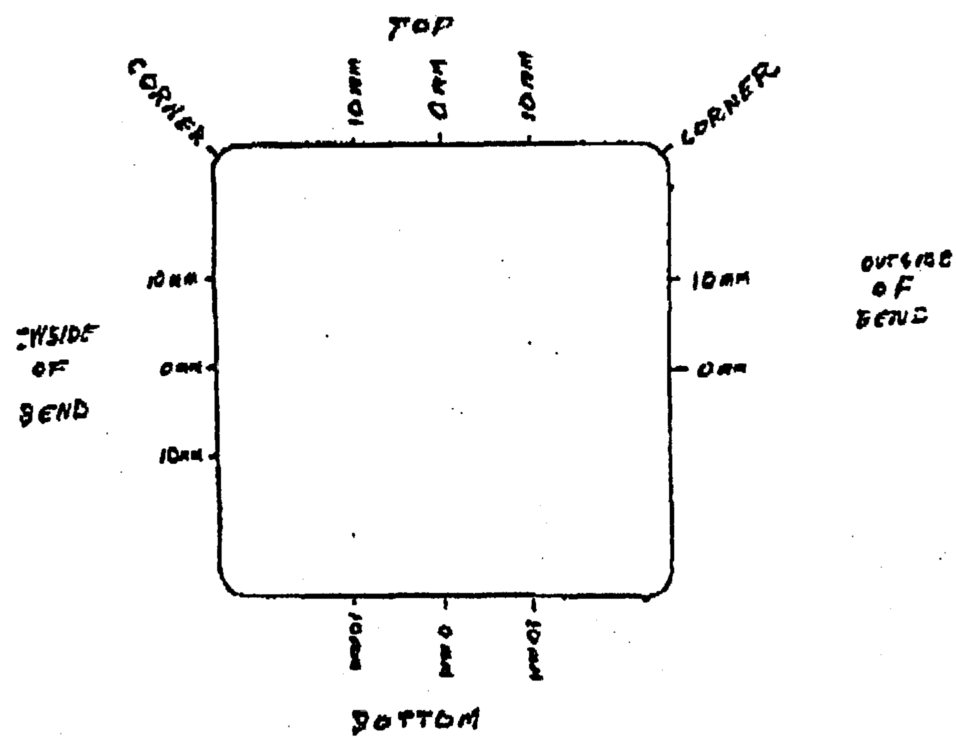
The majority of samples that were measured were cut from CS tubes. The first tests were done on Stage 1 tubes that had been manufactured by machining the extrusion to size rather than drawing the extrusion through a series of dies to reduce it to the final size..

This data is for an early Stage 1 tube machined to size. The ~~machining produced high~~ machining produced high stresses at the surface as can be seen from the ~~data in Table III~~.

GD
5/19/00



Conduit As Machined



Conduit Machined, Compacted and Bent

TABLE III
MACHINED CS CONDUIT

LONGITUDINAL RESIDUAL STRESSES
Mid Length Locations

Specimen	Location	Residual Stresses (MPa) Surface	Residual Stresses (MPa) Sub Surface (0.5mm)	Peak Width (deg) Surface	Peak Width (deg) Sub Surface (0.5mm)
As Machined	0 mm (side)	+832 ± 27	+240 ± 3	3.93	1.20
		+851 ± 27*	+267 ± 4*	3.97	1.20
			+225 ± 3*		1.20
			+276 ± 58**		1.16
	10 mm (side)	+1102 ± 33	+298 ± 10	3.79	1.08
	Corner	+1564 + 42	+432 + 14	4.38	1.84
	10 mm (top)	+1091 ± 32	+284 ± 10	4.02	1.23
	0 mm (top)	+926 ± 31	+110 ± 6	4.66	1.16
Machined, Compacted & Bent ~ .9m Rad	0 mm OB***	+930 ± 30	-12 ± 4	4.70	1.27
	10 mm OB	+732 ± 26	-139 ± 6	3.61	1.13
	Corner OB	+412 ± 20	+13 ± 5	4.01	1.42
	10 mm (top)	+184 ± 15	+8 ± 4	3.88	1.13
	0 mm (top)	-792 ± 25	-234 ± 8	3.39	1.06
	10 mm (top)	+524 ± 22	-61 ± 5	3.96	1.05
	Corner	-626 ± 24	+14 ± 4	3.73	1.26
	10 mm IB***	-51 + 12	+329 + 10	3.55	1.10
	0 mm IB	-116 ± 13	+356 ± 11	3.70	1.14
	10 mm IB	-72 ± 12	+259 ± 9	3.63	1.09
	10 mm (bottom)	-364 ± 17	-150 ± 7	3.24	1.18
	0 mm (bottom)	+605 + 23	-154 ± 7	3.90	1.14
	10 mm (bottom)	+309 ± 16	+8 ± 4	3.62	0.92

* Repeat two-angle measurements
** Multi-angle $Sine^2$(psi) technique
*** OB = Outside of Bend
IB = Inside of Bend

The manufacturing procedure developed during Stage 1 involved the drawing of the extruded tubes to size and finishing with a mill anneal, (950°C). Values are shown below for a, Stage 2, drawn, annealed and compacted CS1 tube and for a Stage 2 CS2 tube as drawn and annealed, as compacted, bent and straightened and after a heat treatment at 650°C for 50 hours. The precipitation of gamma prime, which causes the strength increase occurs quite rapidly at 650°C so the 50 hour heat treatment was expected to show the majority of the effect on the residual stresses. Because some tubes were honed to increase the id clearance a honed tube is also included. Transverse welds, (butt welds), were also examined both before and after bending and straightening.

TABLE IV
CS TUBES - VARIOUS CONDITIONS

LONGITUDINAL RESIDUAL STRESSES
Mid Length Locations

Specimen	Location	Residual Stresses (MPa) Surface	Residual Stresses (MPa) Sub Surface (0.5mm)	Peak Width (deg) Surface	Peak Width (deg) Sub Surface (0.5mm)
CS1 TUBE					
Compacted	od mid wall	+347 ±13	+221 ±8	1.93	1.34
			+222 ±8*		1.39*
			+217 ±9*		1.37*
	id mid wall	-271 +8	-360 ±10	1.31	1.15
			-360 ±10*		1.19*
CS2 TUBES					
Drawn & Annealed	od mid wall	+51 ± 7	+152 ± 6	1.80	0.99
	id mid wall	-120 ± 6	-126 ± 6	1.01	0.92
id Honed	id mid wall	-905 ± 27	-196 ± 6	3.47	0.96
Heat Treated 650°C/50 hrs	od mid wall	-109 ± 8	+103 ± 6	1.96	1.05
Compacted, Bent & Straightened	od Inside Bend	+562 ± 23	+346 ± 11	4.05	1.23
	id Inside Bend	-3 ± 10	-80 ± 5	2.95	1.22
	od Outside Bend	+366 ± 20	+101 + 6	4.29	1.17
	id Outside Bend	-332 ± 17	-34 ± 5	3.52	1.34
Butt Weld Compacted, Bent & Straightened	od Inside Bend	+145 ± 13	+252 ± 9	3.28	1.38
	id Inside Bend	-72 ± 10	-147 ± 6	2.94	1.27
	od Outside Bend	+127 ± 13	+158 ± 7	3.41	1.24
	id Outside Bend	-380 ± 16	-95 ± 6	3.28	1.32

* Repeat measurement

The following are the measurements taken on a compacted and bent tube simulating the conditions in the coil. The sketch shows the location of the measurements. Four samples were examined. First, one bent to a radius of 0.85m. This was examined both on od and id. Subsequently three samples from the same conduit, #64, R~0.8m, one as bent, one bent and shot peened and one bent and shot peened on outer radius only were examined on the od only. A sketch of the positions where the residual stress was measured is shown below. The measurement results are shown in Tables V and VI.

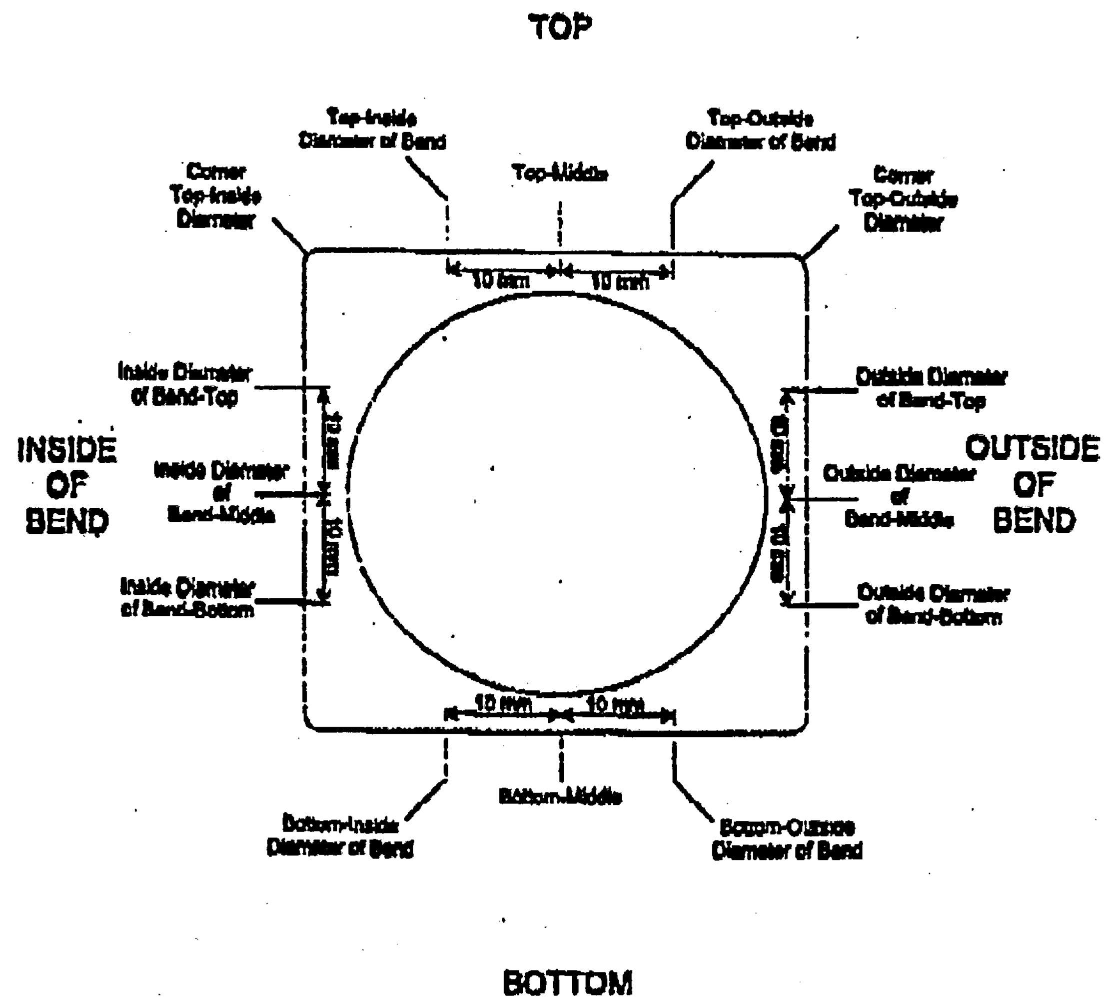


TABLE V
CS2 COMPACTED & BENT

LONGITUDINAL RESIDUAL STRESSES
Mid Length Locations

Specimen	Location	Residual Stresses (MPa) Surface	Residual Stresses (MPa) Sub Surface (0.5mm)	Peak Width (deg) Surface	Peak Width (deg) Sub Surface (0.5mm)
Compacted &Bent R=0.85 m					
id of Tube	Inside Bend	-89 ± 6	-112 ± 7	1.61	1.5
	Outside Bend	-44 ± 6	-7 ± 6	1.63	1.48
od of Tube	OB Bottom*	-6 ± 8	-58 ± 6	2.34	1.32
	OB Middle	+289 ± 14	-9 ± 5	2.64	1.47
	OB Top	+1 ± 8	-74 ± 6	2.38	1.32
	OBCorner Top	-25 ± 7	-36 ± 4	2.00	1.46
	Top Outside	+483 ± 17	+79 ± 6	2.02	1.50
	Top Middle	-236 ± 13	+59 ± 6	2.64	1.51
	Top Inside	-596 ± 19	-39 ± 5	2.52	1.41
	IB Corner Top	-263 ± 13	-70 ± 6	2.30	1.36
	IB Top	-285 ± 14	+196 ± 8	2.80	1.31
	IB Middle	-272 ± 14	+167 ± 8	2.81	1.35
	IB Bottom	-346 ± 15	+192 ± 8	2.87	1.17
	Bottom Inside	-273 ± 11	-37 ± 5	1.81	1.35
	Bottom Middle	-67 ± 8	2 ± 5	2.29	1.47
	Bottom Outside	+75 ± 8	-32 ± 5	1.96	1.47

* OB = Outside of Bend. IB = Inside of Bend

TABLE VI
EFFECT OF SHOT PEENING

LONGITUDINAL RESIDUAL STRESSES
Approximate Mid Length Locations
OD Surface Measurements Only

Specimen	Location	Residual Stresses (MPa)		Peak Width (deg)	
		As Bent	Shot Peened	As Bent	Shot Peened
Tube 64 (63)	OB Bottom*	-2 ± 7	-907 ± 30	2.12	4.19
	OB Middle	-91 + 9	-914 ± 30	2.40	4.09
	OB Top	+12 ± 7	-891 ± 29	1.97	4.08
	OB Corner Top	+86 ± 6	-891 ± 30	1.19	4.29
	Top Outside	+171 ± 9	-944 ± 30	1.84	4.15
	Top Middle	-115 ± 9	-954 ± 31	2.23	4.22
	Top Inside	-193 ± 9	-987 ± 32	1.74	4.45
	IB Corner Top	-37 ± 5	-808 ± 27	1.27	3.64
	IB Top	-48 ± 7	-877 ± 29	2.09	3.95
	IB Middle	-37 ± 7	-885 ± 29	2.06	4.05
	IB Bottom	-60 ± 8	-886 ± 29	2.19	4.04
	Bottom Inside	-240 + 11	-918 ± 30	1.90	4.07
	Bottom Middle	-52 ± 7	934 ± 30	1.85	4.00
	Bottom Outside	+272 ± 12	-945 ± 30	2.02	4.00
Sample Shot Peened Outside of Bend Only	OB Bottom		-873 ± 29		3.99
	OB Middle		-896 ± 29		4.11
	OB Top		-829 ± 28		4.09

* OB = Outside Bend, IB = Inside Bend

While the majority of the work was done on CS tubing TF tubing was also examined. The measurement data is shown below in Table VII.

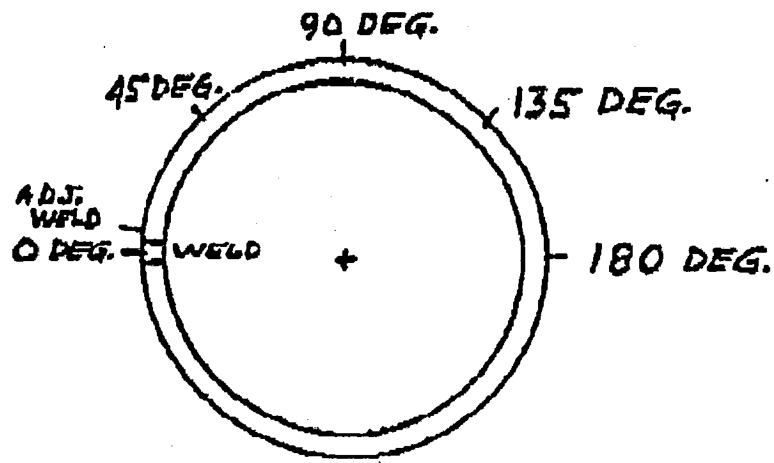


TABLE VII
TF TUBES

LONGITUDINAL RESIDUAL STRESSES
Mid Length locations

Specimen	Location	Residual Stresses (MPa) Surface	Residual Stresses (MPa) Sub Surface	Peak Width (deg) Surface	Peak Width (deg) Sub Surface
TF SAMPLES					
TF2 Sample	Weld Line	+187 ± 9	--	1.82	--
	Adj Weld line	+142 ± 9	--	2.10	--
	45° from weld	+243 ± 10	--	1.87	--
	90° from weld	+254 ± 10	--	1.82	--
	135° from weld	+240 ± 10	--	1.83	--
	180° from weld	+348 ± 13	--	1.93	--
TF2 compacted	od 0°	+513 ± 17	+474 ± 14*	2.33	1.37
Xverse weld (Butt Weld)	od 90°	+474 ± 16	+437 ± 13*	2.16	1.31
TF2 compacted	id 0°	-573 ± 17	-325 ± 9*	2.34	1.20
Xverse weld (Butt Weld)	id 90°	-881 ± 23	-492 ± 12*	2.62	1.29
TF1 compacted	od 0°	-517 ± 18	-165 ± 8*	2.70	1.38
bent & straightened	od 90°	+94 ± 8	+140 ± 7	2.16	1.38

* 0.25mm deep

TABLE VIII
RESIDUAL STRESS MEASUREMENTS
TRANSVERSE DIRECTION
SAMPLES PROVIDED BY
INCO ALLOYS INTERNATIONAL, INC.

Heat	Condition	Size odxid	od Stress (MPa) od	-.025	-.15	-.38	-.76 mm	id Stress (MPa) -.76 mm	-.38	-.15	-.025	id
HW0530CK	Annealed	57x42mm Square	Coarse grained, no measurements					-83	-41	-83	-97	-366
HWO530CK	Drawn 22% (Cu Plated)	53x41 Square	-12	-117	-34	+110	+28	-166	-262	-248	-234	-324
HW0530CK	Sunk 20%	48x36 Square	-193	-228	-145	-62	-55	Not Determined				
HW0550CK	Mandrel Draw 36%	49x39 Square	-62	+14	-3.4	-48	-90	Not Determined				
Y5402K	Mandrel Draw	43x38 Round	-48	+214	+248	+262	+255	Not Determined				
HW0583CK	Pilgered 55%	64x49 Round	+34	+28	+55	+103	+110	-179	-172	-172	-207	-255
HW0583CK	Annealed	64x49 Round	-345	-297	-28	-124	-103	-83	+21	+21	+7	-407
Y9402K	Sunk + Mandrel Draw 24%	52x38 Rectangle	-28	+34	+34	+103	+193	Not Determined				
HW0520CK	Tube Mill Sunk* Turkshead	15x14 Rectangle	+248	+290	+317	+159	+90	Not Determined				

* Produced at Gibson Tube

CONCLUSIONS

While shot peening of the od and honing of the id produced compressive stresses the samples machined to size had high tensile stresses on the od.

On bent conduits the stress was strongly dependent on the location on the wall of the conduit.

Shot peening of the od surface produces a strongly compressive stress on the surface, but there was limited penetration.

Id surfaces generally had either compressive or low tensile stresses. Honing the id produced high compressive stresses.

TABLE IX

SAMPLE IDENTIFICATION AND NOMINAL DIMENSIONS

US/DPC sample	23mm square hollow cross-section x 241 mm long
PTF as compacted	48 mm od x 254 mm long
PTF shot peened	48 mm od x 254 mm long
CS1 machined	51 mm square od, round id x 241 mm long
CS1 machined & compacted	51 mm square od, round id x 241 mm long
CS2 drawn & annealed	45 mm square x 39 mm id x 112 mm long
CS2 id honed	45 mm square x 39 mm id x 112 mm long
CS2 heat treated 650°C	48 mm square x 39 mm id x 127 mm long
CS2 compacted & bent	46 mm square x 36 mm id x 193 mm long
CS2 butt weld compacted and bent	46 mm square x 36 mm id x 193 mm long
CS2 compacted & bent	45mm square x 37 mm id x 191 mm long
64(63) compacted and bent	45 mm square x 37 mm id x 117 mm long
64(63) shot peened	45 mm square x 37 mm id x 121 mm long
64(63) peened outside of bend only	45 mm square x 37 mm id x 62 mm long
TF2 sample from RF	38mm od x 1mm wall x 300mm long
TF2 compacted butt weld	41 mm od x 38 mm id x 149 mm long
TF2 bent & straightened	41 mm od x 38 mm id x 205 mm long

TABLE X
MEASUREMENT LOCATIONS

US/DPC sample	see Table I
PTF as compacted	see Table II
PTF shot peened	see Table II
CS1 machined	see Table III
CS1 machined & compacted	see Table III
CS2 drawn & annealed	73 mm from end and midwidth on outside, 50 mm from end on id
CS2 id honed	42 mm from end on id
CS2 heat treated 650°C	50 mm from end and mid width on outside
CS2 compacted & bent	79 mm from end and mid width on outside and inside of bend on outside of tube
CS2 butt weld compacted and bent	37 mm from end and midwidth at outside and inside of the bend on the outside of tube
CS2 compacted & bent	40 mm from end of tube at inside and outside of bend on inside of tube 70 mm from end of tube on the outside of tube
64(63) compacted and bent	70 mm from vibratooled end on the outside
64(63) shot peened	mid length on the outside of tube
64(63) peened outside of bend only	mid length on outside of bend on the outside of tube
TF2 sample from RF	see Table VII
TF2 compacted butt weld	mid length at 0° and 90° inside and outside of tube
TF2 bent & straightened	75 mm from end of tube on the outside 55 mm from end of tube at 0° position and 60 mm from end at 90° position on inside of tube