PFC/RR-94-2

Incoloy Alloy 908 Data Handbook

L.S. Toma, M.M. Steeves, R.P. Reed *

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Superconducting Magnet Development Group
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA

* Cryogenic Materials Inc.
2625 Iliff, Boulder CO 80303 USA

ABSTRACT

This handbook is a compilation of all available properties of Incoloy alloy 908 as of March, 1994. Data included in this paper cover mechanical, elastic, thermal and magnetic characteristics. The mechanical properties include tensile, fracture toughness, fatigue, and stress-rupture for both the base metal and related weld filler metals. Elastic properties listed are Young's, shear and bulk moduli and Poisson's ratio. Thermal expansion, thermal conductivity and specific heat and magnetization are also reported. Data presented are summarized in the main body and presented in detail in the supplements. Areas of ongoing research are briefly described, and topics for future research are suggested. The data have been compiled to assist in the design of large-scale superconducting magnets for fusion reactors.

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139-4294
Telephone: 617/253-8100

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TO: All holders of PFC/RR-94-2 *Incoloy Alloy 908 Database Handbook,* by L.S. Toma, et al.

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ERRATUM

PFC/RR-94-2 contains the following errors (as cited by the author):

Close examination of the magnetic properties section of the Handbook has revealed errors in the tabulated data column headings and in the horizontal axis labels on the figures showing the data. Please make the necessary corrections to the report in accordance with the attached ERRATA sheet.

October 11, 1994

PFC/RR-94-2

Incoloy Alloy 908 Handbook

ERRATA

page 30 - Replace the column headings in the table for columns one and three with "H(MA/m)."

page 31 - Replace the horizontal axis label in Figure 19 with "H(MA/m)."

page 32 - Replace the column headings in the table for columns one and three with "H(MA/m)."

page 33 - Replace the horizontal axis label in Figure 20 with "H(MA/m)."

CONTENTS

General Characteristics

Density at 293 K:	8.08 g/cm^3	(INCO Preliminary Data Sheet, 1993)
	8.128 g/cm^3	(Ledbetter, 1990)
	8.113 g/cm^3	(Ledbetter, 1990)
Melting Point	1634-1683 K	(Wyrick, 1993)
Magnetic state:	Curie point: ferromagnetic-paramagnetic transition temperature	
	555 K longitudinal	(INCO Preliminary Data Sheet, 1993)
	559 K transverse	
Aged structure:		(Morra et al., 1992)

Predominant phases	Approximate volume (%)	Structure	Lattice Parameter	Particle size (μm)
γ	80	fcc	0.360	
γ' $(Ni,Fe)_3Al,Ti,Nb$	20	fcc (ordered)	0.359	10-50

Annealing (intermediate, final) temperature:	980°C (5-60 minutes, rapid cooling)
Solution annealing (to dissolve γ' strengthening phase)	1050°C / 1 hour
Aging temperature range:	595-815°C
Typical grain size	
following cold work	25-35 μm
following annealing	80-135 μm
Hardness (following mill anneal, hot / cold work, 700°C/50h aging, air cooling)	39-40 R_C

Composition:

Element	Proposed requirements	Target (including trace elements)
Fe	balance	40.7
Ni	47.0-51.0	49.5
Cr	3.75-4.5	3.9
Nb	2.7-3.3	3.0
Ti	1.2-1.8	1.6
Al	0.75-1.25	1.0
Si	0.3 maximum	0.15
Mn	1.0 maximum	0.04
C	0.03 maximum	0.01
Cu	0.5 maximum	0.01
P	0.015 maximum	0.003
B	0.012 maximum	0.003
S	0.005 maximum	0.001
Mo	-	0.02
Co	0.1 maximum	0
Ta	-	0.01
O	-	0.001
N	-	0.002

Mechanical Properties

Tensile Yield Strength

Condition:	Tensile Yield Strength (MPa) * 298 K	77 K	4 K
MA	389	662	662
MA + 0% CW + 650°C/200 h **	1075 (±41)	1189 (±17)	1227 (±14)
MA + 20% CW + 650°C/180 h (T)	-	-	1466 (±26)
MA + 20% CW + 650°C/200 h	1279 (±10)	-	1489 (±28)
MA + 0% CW + 700°C/100 h	1103 (±0)	1192 (±0)	1258 (±31)
MA + 20% CW + 700°C/100 h	1241 (±14)	-	1434 (±7)
MA + 0% CW + 750°C/50 h	1041 (±7)	1117 (±7)	1199 (±14)
MA + 20% CW + 750°C/50 h	1248	-	1320 (±3)
MA + Extrude + Tube reduce + Anneal + CD + Hydrogen anneal + 12-14% CD + 650°C/200 h (L)	997 (±23)	1102 (±33)	1155 (±35)

MA = mill annealed (980°C/1 hour); CW = cold worked; CD = cold drawn;
T = transverse to rolling direction; L = longitudinal with respect to rolling direction

* Defined at 0.2% offset.

** Unless otherwise specified, all aging in vacuum.

Most data shown above have been reported by Hwang et al. (1992). The tensile yield strength at 4 K for the alloy that was mill-annealed, 20% cold worked, and aged at 650°C for 180 hours represents the average from 8 tests on 3 and 10 mm thick plate (Tobler, 1993). In all other cases, except the 298 K values of 1248 MPa (single datum point) and 997 MPa (3 data points), the values represent the average of 2 tests. Additional tensile data for other conditions are presented in Supplement 2.

The tensile yield strength and hardness are very sensitive to thermomechanical treatment parameters. In Supplement 3 are presented the effects of temperature, time, cooling rates, and cold work on hardness as well as typical grain sizes that result from the various thermomechanical treatments. The effects of processing, as measured by Gleeble hot ductility, are contained in Supplement 4.

Mechanical Properties

Tensile Ultimate Strength

Condition:	Tensile Ultimate Strength (MPa) 298 K	77 K	4 K
MA	717	1082	1130
MA + 0% CW + 650°C/200 h	1433 (±0)	1664 (±38)	1892 (±31)
MA + 20% CW + 650°C/180 h (T)	-	-	1900 (±60)
MA + 20% CW + 650°C/200 h	1499 (±17)	-	1903 (±14)
MA + 0% CW + 700°C/100 h	1396 (±4)	1682 (±0)	1883 (±0)
MA + 20% CW + 700°C/100 h	1451 (±3)	-	1882 (±14)
MA + 0% CW + 750°C/50 h	1344 (±21)	1603 (±18)	1878 (±121)
MA + 20% CW + 750°C/50 h	1413	-	1799 (±0)
MA + Extrude + Tube reduce + Anneal + CD + Hydrogen anneal + 12-14% CD + 650°C/200 h (L)	1250 (±20)	1540 (±0)	1660 (±25)

MA = mill annealed; CW = cold worked; T = transverse; L = longitudinal; CD = cold drawn

Most data shown above have been reported by Hwang et al. (1992). The data for the material that was mill-annealed, 20% cold worked, and aged at 650°C for 180 hours represents the average from 7 tests at 4 Kelvins on 3 and 10 mm thick plate (Tobler, 1993). In all other cases, the values shown above represent the average of 2 tests, except for the 298 K values of 1413 MPa (1 test) and 1250 MPa (3 tests). Additional data for other conditions are presented in Supplement 2.

Mechanical Properties

Tensile Elongation (%)

Condition:	Tensile Elongation (%) 298 K	77 K	4 K
MA + 0% CW + 650°C/200 h	16.5 (±1)	21.5 (±0.5)	28.5 (±1.4)
MA + 20% CW + 650°C/180 h (T)	-	-	16 (±2)
MA + 20% CW + 650°C/200 h	19 (±1)	-	24 (±0.5)
MA + 0% CW + 700°C/100 h	15 (±0.5)	24 (±0)	26 (±2.5)
MA + 20% CW + 700°C/100 h	21 (±1)	-	27 (±0.4)
MA + 0% CW + 750°C/50 h	16 (±0)	26 (±0.5)	26 (±0.5)
MA + 20% CW + 750°C/50 h (T)	17	-	26.5 (±1.5)
MA + Extrude + Tube reduce + Anneal + CD + Hydrogen anneal + 12-14% CD + 650°C/200 h (L)	21 (±2)	29 (±4)	24 (±2)

MA = mill annealed; CW = cold worked; T = transverse; L = longitudinal; CD = cold drawn

Most data shown above have been reported by Hwang et al. (1992). The 4 K data for the material that was mill-annealed, 20% cold worked, and aged at 650°C for 180 hours represent 7 tests on specimens cut from 3 mm (flat) and 10 mm (round) plate (Tobler, 1993). All other data represent 2 tests , except the 298 K values of 17% (1 test) and 21% (3 tests). Elongation values depend on specimen geometry and strain rate. Additional data for other conditions are provided in Supplement 2. Reduction-of-area data are also summarized in Supplement 2.

Mechanical Properties

Tensile Stress-Strain Curves

Tensile engineering stress-strain curves for Incoloy 908 are dependent on the material's thermomechanical conditioning and strain rate. Room temperature strain-controlled stress-strain curves for three different aging conditions (650°C/200 h, 700°C/100 h, 750°C/50 h) are compared in Figure 1. Figures 2-4 show the results of load-controlled cryogenic tests of these same three heat treatment conditions.

Mechanical Properties

Tensile Stress-Strain Curves

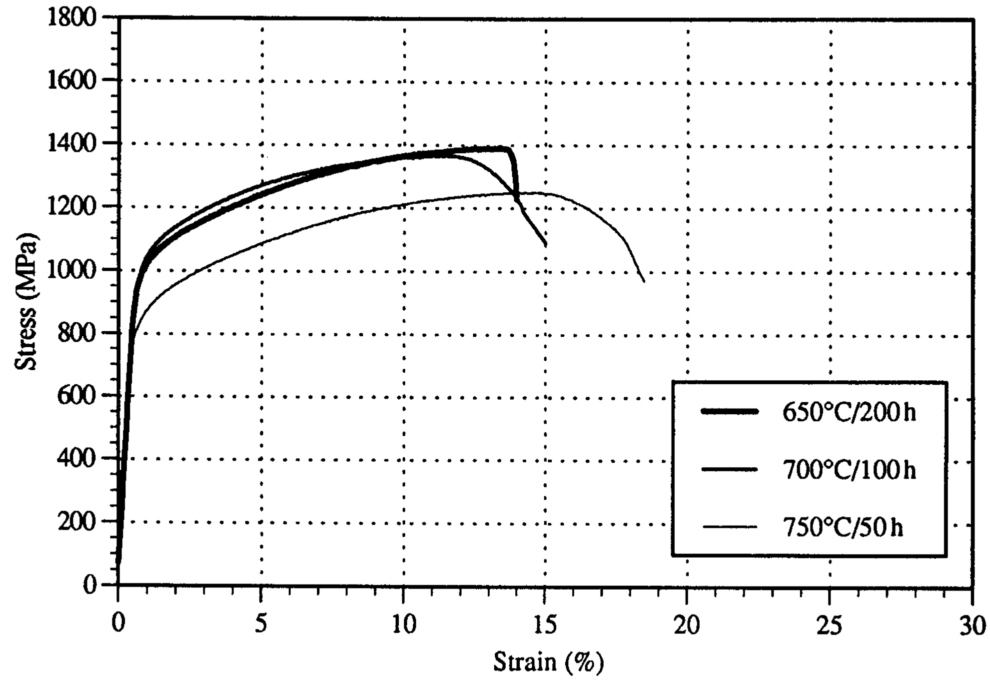

Figure 1. Stress-strain curves as a function of heat treatment. Tests were conducted at 298 K. Strain rate = 1×10^{-4} m/m · s^{-1} (Morra, 1986).

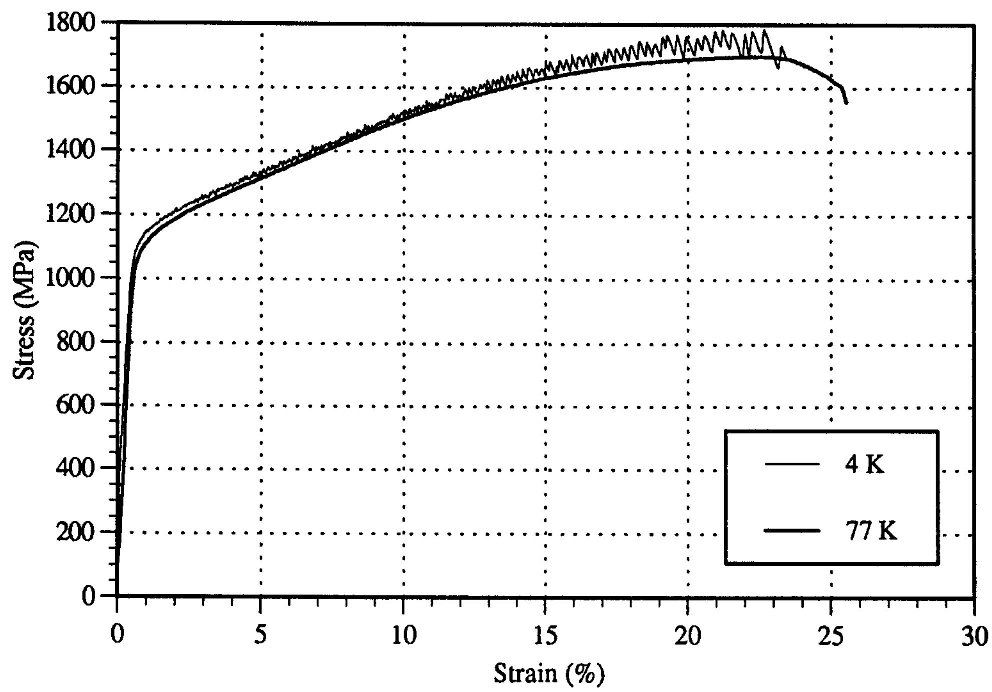

Figure 2. Stress-strain curves for 650°C/200 h aged Incoloy 908 at 4 and 77 Kelvins. Loading rate = 45.3 grams · s^{-1} [0.1 lb · s^{-1}] (Martin, 1986).

Mechanical Properties **Tensile Stress-Strain Curves**

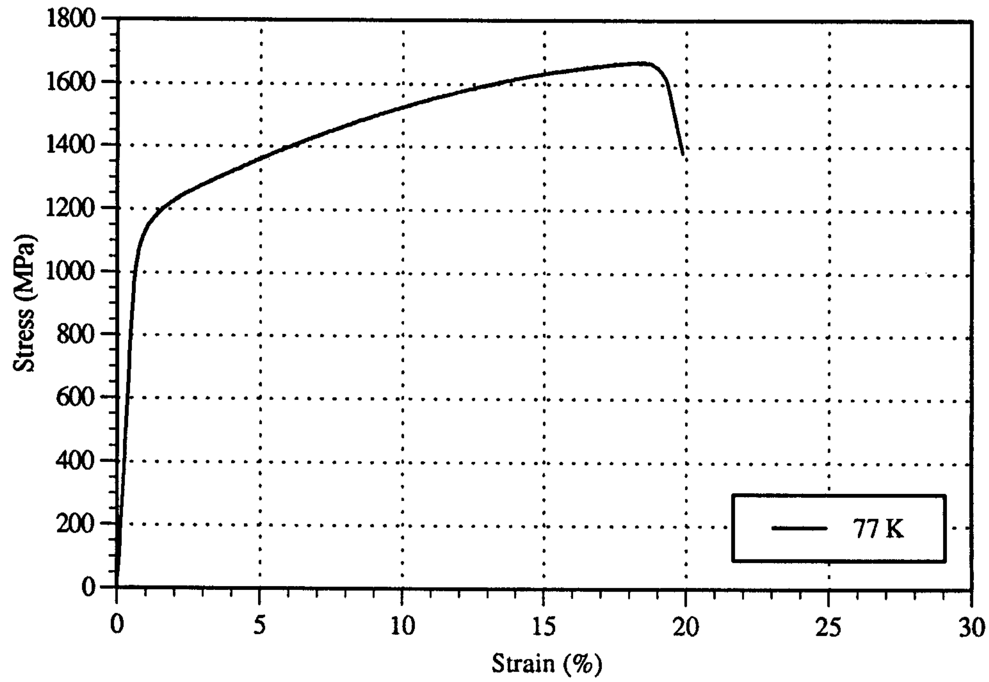

Figure 3. Stress-strain curves for 700°C/100 h aged Incoloy 908 at 77 Kelvins. Loading rate = 45.3 grams · s^{-1} [0.1 lb · s^{-1}] (Martin, 1986).

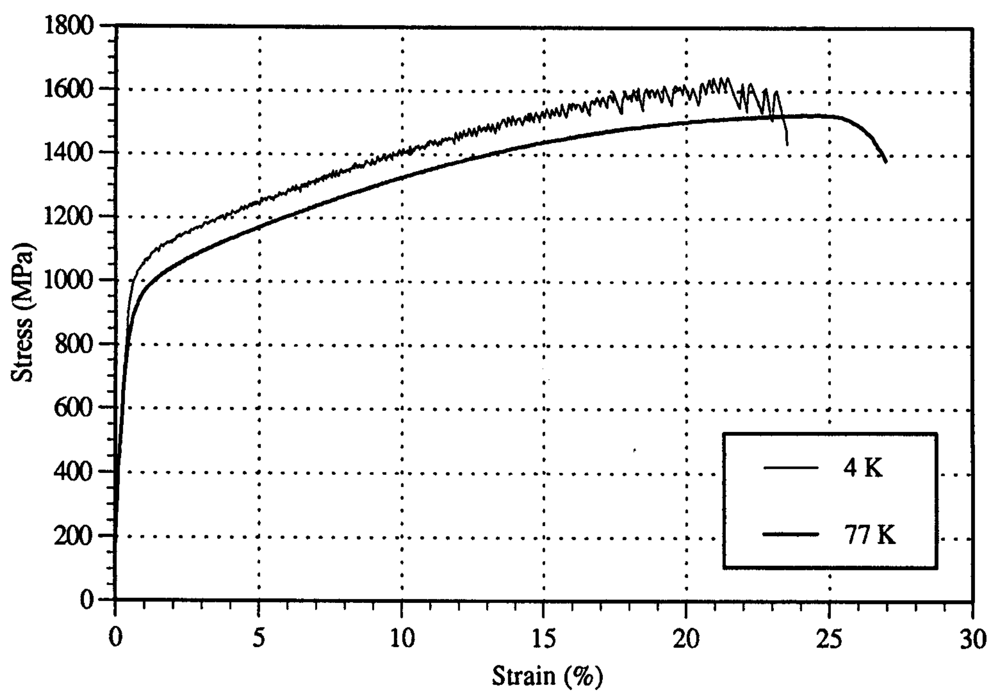

Figure 4. Stress-strain curves for 750°C/50 h aged Incoloy 908 at 4 and 77 Kelvins. Loading rate = 45.3 grams · s^{-1} [0.1 lb · s^{-1}] (Martin, 1986).

Mechanical Properties

Fracture Toughness

Condition:	Fracture Toughness ($MPa \cdot m^{1/2}$) 298 K	77 K	4 K
MA + 20% CW (TL)	-	-	265
MA + 20% CW + 650°C/200 h (TL)	-	-	155 (±25)
MA + 0% CW + 650°C/200 h	196 (±5)	243 (±6)	235 (±5)
MA + 0% CW + 700°C/100 h	176 (±5)	219 (±5)	220 (±2)
MA + 0% CW + 750°C/50 h	160 (±0)	211 (±1)	240 (±4)
Extruded + tube reduced + annealed + CD + hydrogen annealed + 8.5% CW + 650°C/200 h (LT) - Conduit production run	185 (±14)	203 (±3)	196 (±3)
Weld fracture toughness values *			
MA + 0% CW, GTAW with 908 filler + 650°C/200 h	106 (±8)	-	105 (±1)
MA + 0% CW, GTAW with 9HA filler + 650°C/200 h	168 (±9)	-	150
MA + 9% CW, GTAW with 9HA filler + 650°C/200 h	168	-	130 (±10)

MA = mill annealed; CW = cold worked; TL, LT = crack orientation in compact-tension specimens;
SA = solution annealed; CD = cold drawn; GTAW = gas tungsten arc weld
* More weld data is presented in Supplement 10, Weld Metal Properties

Limited GTA weld data from an MIT program and Hwang et al. (1992) are included in the table. The strengths and toughnesses are very dependent on the composition of the weld filler. See Jang et al. (1994) for more details.

Fracture toughness tests on base metal were J-integral tests with J-critical converted to plane-strain fracture toughness [$K_{IC}(J)$]. Good correlation exists between the fracture toughness and the yield strength (σ_y): the fracture toughness decreases linearly with increasing tensile yield strength at constant temperature.

Mechanical Properties

Stress-Controlled Fatigue

For Incoloy 908 base metal that has been mill annealed, 0% cold worked, aged at 700C for 50 hours, and flash welded, stress-controlled fatigue data at 7 K (*R* = 0.1) from Nyilas et al. (1992) are presented in Figure 5. The frequency of the stress cycles was 20 Hz. Due to the very limited data, no fatigue strengths have been estimated.

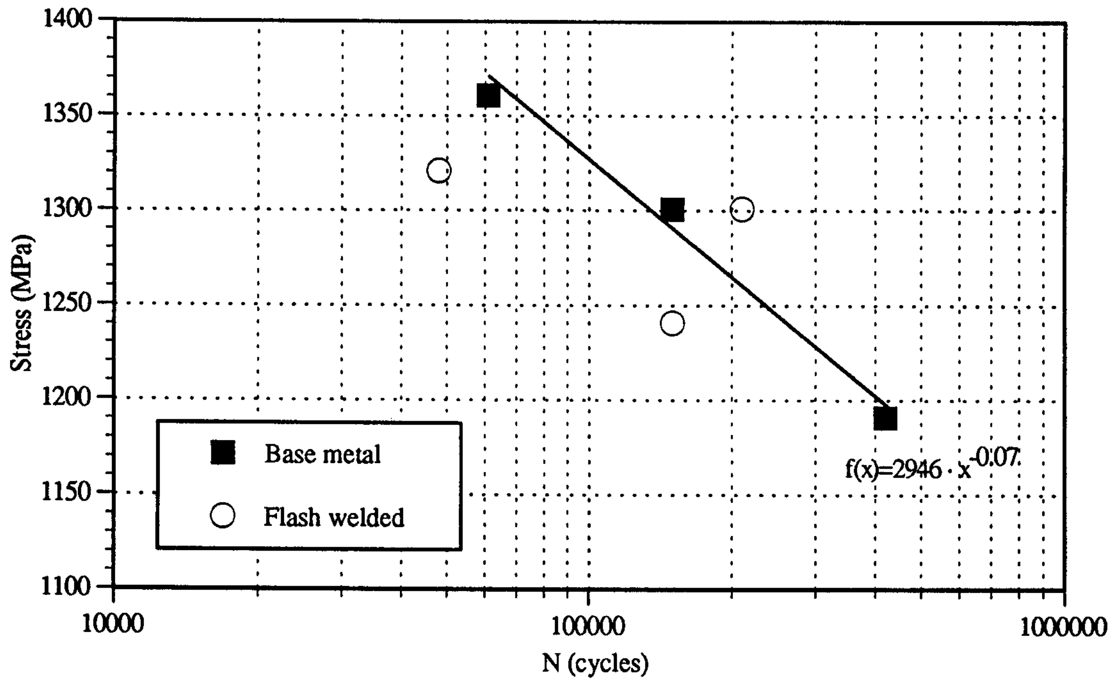

Figure 5. Fatigue-life results at 7 K of smooth cylindrical specimens with base metals and flash butt weldments at R=0.1. Condition: mill annealed and aged 700°C for 50 hours (Nyilas, et al., 1992).

Mechanical Properties

Fatigue Crack-Growth Rate

Fatigue crack-growth rates (*da/dN*) have been measured for a number of conditions of Incoloy 908. In general, at intermediate values of the stress-intensity factor change (ΔK) there is a linear dependence of the log of *da/dN* versus the log of ΔK. This dependence is called the Paris Law:

$$da/dN = C \cdot (\Delta K)^n$$

where C and *n* are constants. The values of C and *n* are presented in the accompanying table for various conditions and temperatures.

Condition		C × 10^{-12} (m/cycle) 298 K	C × 10^{-12} (m/cycle) 4 K	*n* 298 K	*n* 4 K	Source
MA + 0% CW + 650°C/200 h		1.97	1.50	3.03	3.41	Hwang et al. (1992)
MA + 0% CW + 700°C/50 h		-	0.39 ‡ (±0.35)	-	3.68 ‡ (±0.10)	Nyilas (1990)
MA + 0% CW + 700°C/100 h		8.72	0.695	2.95	3.38	Hwang et al. (1992)
MA + 0% CW + 700°C/100 h		2.97 †	2.13	3.19 †	3.03	Martin et al. (1988)
MA + 0% CW + 750°C/50 h		18.5	1.11	2.76	3.18	Hwang et al. (1992)
MA + 0% CW + 750°C/50 h		3.49 †	1.56	3.25 †	3.22	Martin et al. (1988)
MA + 20% CW + 650°C/200 h		0.273	0.07	3.79	4.06	Hwang et al. (1992)
MA + 20% CW + 700°C/100 h		2.58	1.99	3.25	3.04	Hwang et al. (1992)
MA + 20% CW + 750°C/50 h		3.49	0.77	3.25	3.45	Hwang et al. (1992)
MA + 20% CW + 200°C/24 h + 340°C/48 h + 660°C/72 h + 725°C/12 h	SC	33.6	5.30 *	2.49	3.10 *	Mei et al. (1994)
	LC	33.6	0.04 *	2.49	4.68 *	

MA = mill annealed; SA = solution annealed; CW = cold worked;
SC = short-crack test procedure; LC = long-crack test procedure (standard)
* Tests conducted at 77 K
† Measured at 273 K
‡ Measured at 7-20 K; R = 0.1, 0.7

Figures of *da/dN* versus ΔK for some of the conditions and temperatures given in this table are shown in the following pages. Individual data points for each curve are included in Supplement 5.

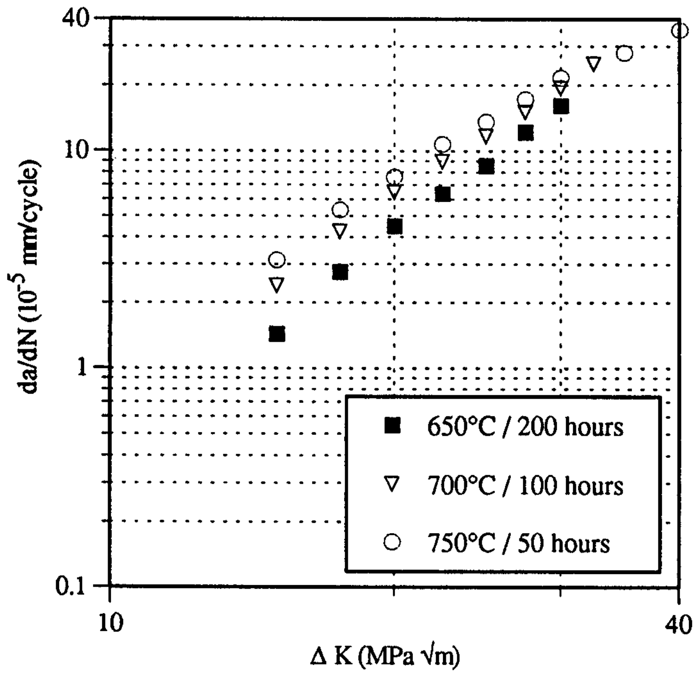

Figure 6. Fatigue crack growth rate at 298 K for the mill annealed and aged condition. (Hwang, et al., 1992)

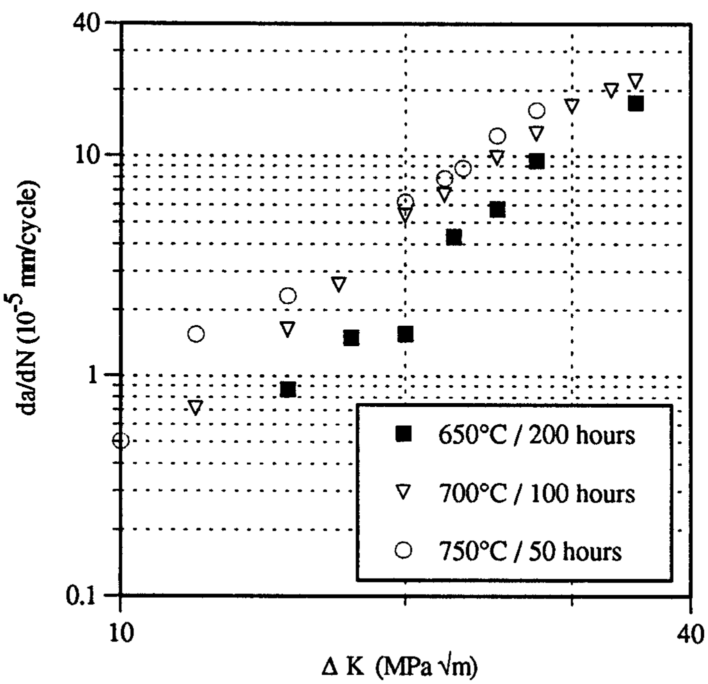

Figure 7. Fatigue crack growth rate at 298 K for the mill annealed, 20% cold worked and aged condition. (Hwang, et al., 1992)

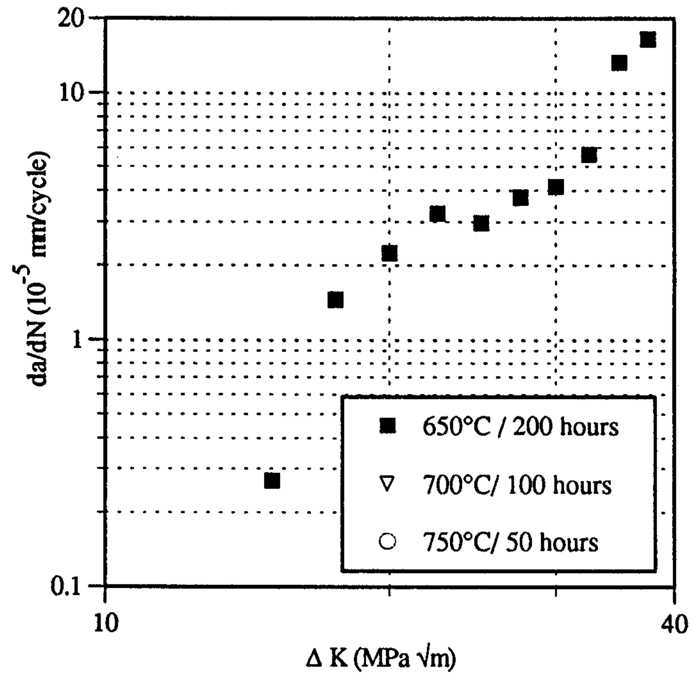

Figure 8. Fatigue crack growth rate at 77 K for the mill annealed and aged condition. (Hwang, 1992)

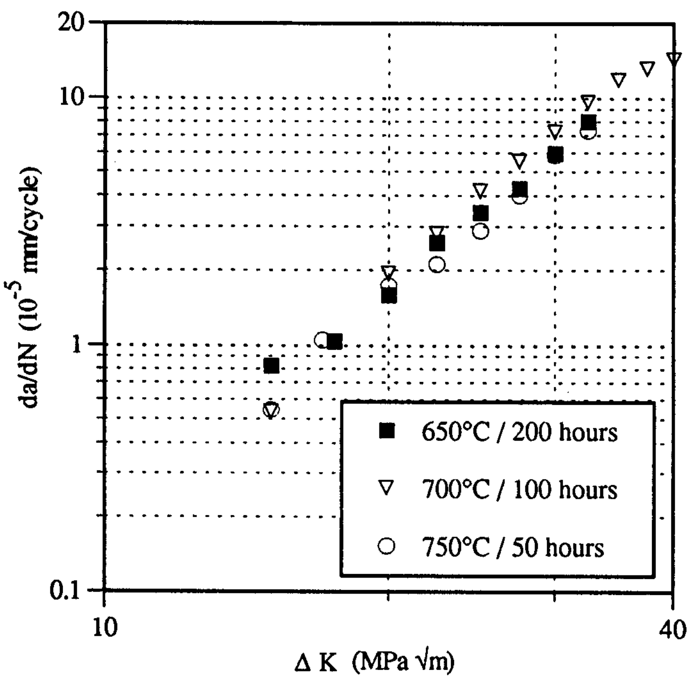

Figure 9. Fatigue crack growth rate at 4 K for the mill annealed and aged condition. (Hwang, et al., 1992)

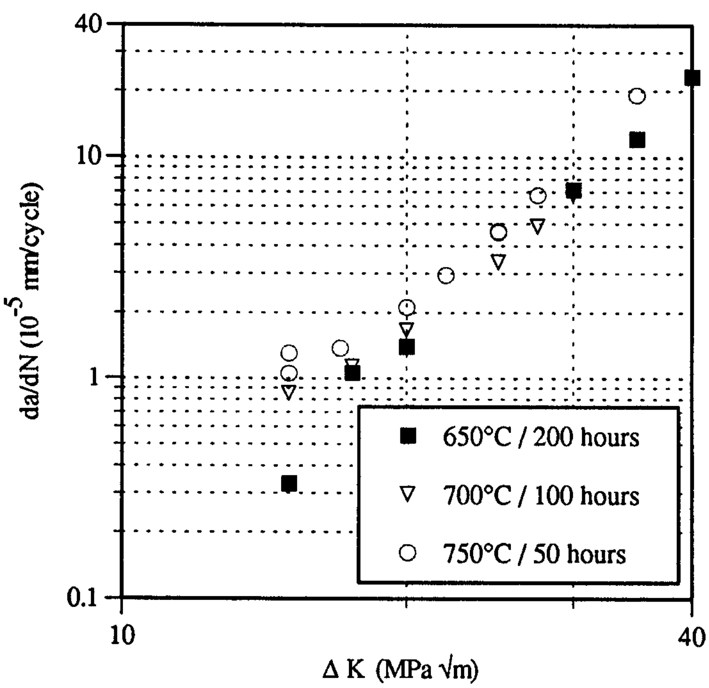

Figure 10. Fatigue crack growth rate at 4 K for the mill annealed, 20% cold worked and aged condition. (Hwang, et al., 1992)

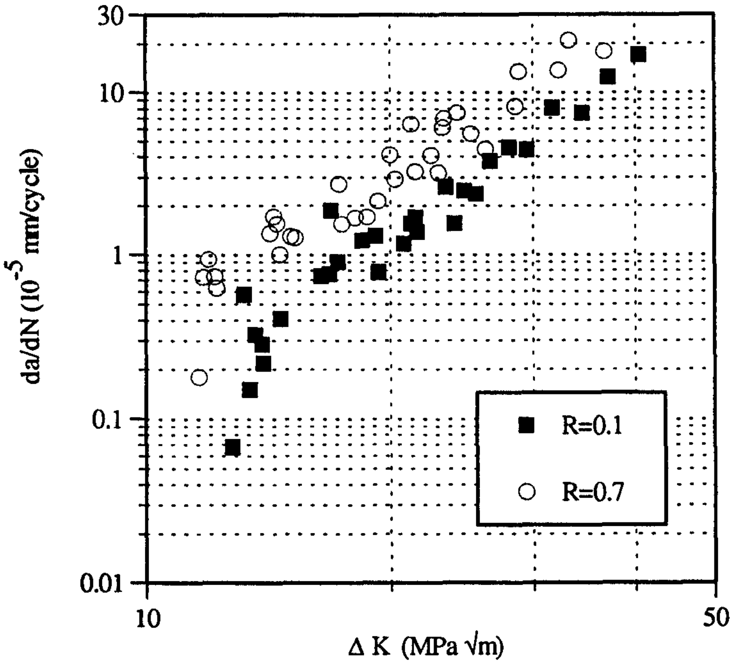

Figure 11. Fatigue crack growth rate at 7-20 K for the mill annealed and 700°C/50 hour aged condition. (Nyilas, et al.)

Mechanical Properties

Fatigue Crack-Growth Rate

Tobler and Hwang (1994) have reported data from compact tensile specimens from 3 mm and 10 mm plate to crack-growth rate levels of 10^{-10} m/cycle; ΔK values at this low crack-growth rate are referred to as threshold values (ΔK_{th}). The variability of the extrapolated value, considering data spread, was estimated at about ±10%. The short-crack technique (constant K_{max}) was used. Mei et al. (1994) also measured threshold values and used both the short-crack and the more conventional long-crack techniques of decreasing K_{max} with $R = 0.05$. Their data are summarized below.

		ΔK_{th} (MPa · m$^{1/2}$)		
Condition:	Technique	298 K	77 K	4 K
MA, 20% CW, 650°C/180 h	SC	2	4	9
MA, 20% CW, plate and as processed, unaged conduit		-	4	-
MA, 20% CW, 200°C/24 h, 340°C/48 h, 660°C/72 h, 725°C/12 h	SC	3	4	-
	LC	4	7	-

MA = mill annealed; CW = cold worked;
SC = short-crack test procedure; LC = long-crack test procedure (standard)

Mechanical Properties

Stress Rupture
Air Atmosphere

Stress-rupture data have been obtained by Morra (1994), Morra et al. (1994), and Weber and Sizek (1993) to study stress-accelerated grain-boundary oxidation (SAGBO) of Incoloy 908 during high-temperature heat treatments. These data are presented in tabular and graphical formats below. Sheet and bar specimens were double-edge notched with stress concentrations (K_t) of 4.5 and 4.1, respectively.

Rupture describes failure by a combination of creep and SAGBO damage. Ductile failure is caused by creep alone, and denotes that SAGBO did not play a role. Tests in which failure did not occur are represented by a dash. These tests were interrupted prior to failure.

Temp. (°C)	Atm.	Cold Work	Stress (MPa)	Time to Failure (h)	Failure Type	Oxygen (ppm)	Water (ppm)	Source
450	air	-	625	322	rupture			Morra et al. (1994)
540	air	-	520	41.0	rupture			Morra et al. (1994)
		-	526	28.1	rupture			Morra et al. (1994)
		-	565	4.70	rupture			Morra et al. (1994)
		-	600	6.22	rupture			Morra (1994)
		-	624	3.40	rupture			Morra et al. (1994)
550	air	5 %	603	>24.0	rupture			Weber and Sizek (1993)
		5 %	633	37.4	rupture			Weber and Sizek (1993)
		5 %	663	22.0	rupture			Weber and Sizek (1993)
650	air	-	222	>1000	-			Morra et al. (1994)
		-	297	0.78	rupture			Morra et al. (1994)
		-	300	>1200	-			Morra et al. (1994)
		-	310	0.33	rupture			Morra et al. (1994)
		-	330	0.29	rupture			Morra et al. (1994)
		-	350	0.50	rupture			Morra et al. (1994)
		-	350	13.8	rupture			Morra et al. (1994)
		5 %	362	>100	-			Weber and Sizek (1993)
		-	400	0.28	rupture			Morra et al. (1994)
		-	460	0.20	rupture			Morra et al. (1994)
		5 %	483	0.40	rupture			Weber and Sizek (1993)
		5 %	543	0.80	rupture			Weber and Sizek (1993)
		-	547	0.10	rupture			Morra et al. (1994)
		5 %	573	0.80	rupture			Weber and Sizek (1993)
		5 %	603	0.50	rupture			Weber and Sizek (1993)
		-	625	0.10	rupture			Morra et al. (1994)
		5 %	637	0.20	rupture			Weber and Sizek (1993)
		5 %	717	0.30	rupture			Weber and Sizek (1993)
		5 %	797	>0.10	rupture			Weber and Sizek (1993)

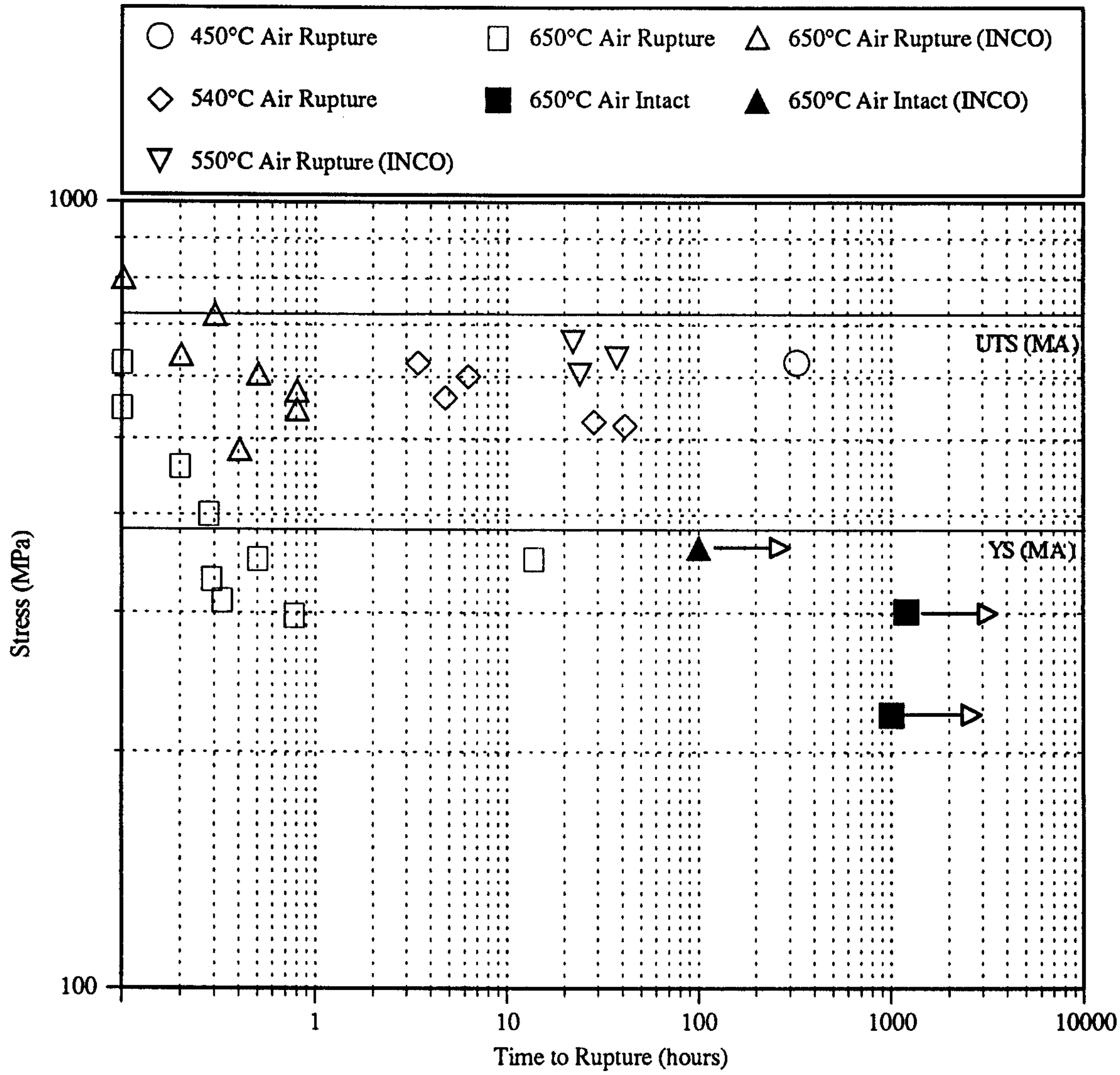

Figure 12. Stress rupture data from tests on alloy 908 performed in air (1 atm). Arrows indicate that the test was interrupted and that the sample did not fail at the time shown. Lines are superimposed showing the tensile properties for unaged material in the mill-annealed condition (YS=389 MPa, UTS=717 MPa). From Morra et al. (1994).

Mechanical Properties

Stress Rupture
Argon Atmosphere

Rupture describes failure by a combination of creep and SAGBO damage. Ductile failure is caused by creep alone, and denotes that SAGBO did not play a role. Tests in which failure did not occur are represented by a dash. These tests were interrupted prior to failure.

Temp. (°C)	Atm.	Cold Work	Stress (MPa)	Time to Failure (h)	Failure Type	Oxygen (ppm)	Water (ppm)	Source
550	argon	-	650	>478	-	1.0	10	Morra (1994)
650	argon	-	550	>211	-	0.5		Morra et al. (1994)
		-	550	452.5	rupture	0.5	10	Morra et al. (1994)
		-	550	522	-	0.5	10	Morra et al. (1994)
		-	650	44.0	rupture	53		Morra et al. (1994)
		-	650	>61.5	-	6.0		Morra et al. (1994)
		-	650	71.7	rupture	0.5	10	Morra (1994)
		-	650	82.4	rupture	6.0		Morra et al. (1994)
		-	650	142	rupture	0.5	10	Morra (1994)
		-	650	174	rupture	0.5	10	Morra (1994)
		-	720	>71.9	-	0.04		Morra et al. (1994)
		-	720	96.7	*ductile*	<0.01		Morra et al. (1994)
700	argon	-	550	27.0	*ductile*	0.5	10	Morra et al. (1994)
		-	600	22.2	*ductile*	<0.01		Morra et al. (1994)
		-	650	3.45	rupture	53		Morra et al. (1994)

Mechanical Properties | **Stress Rupture Argon Atmosphere**

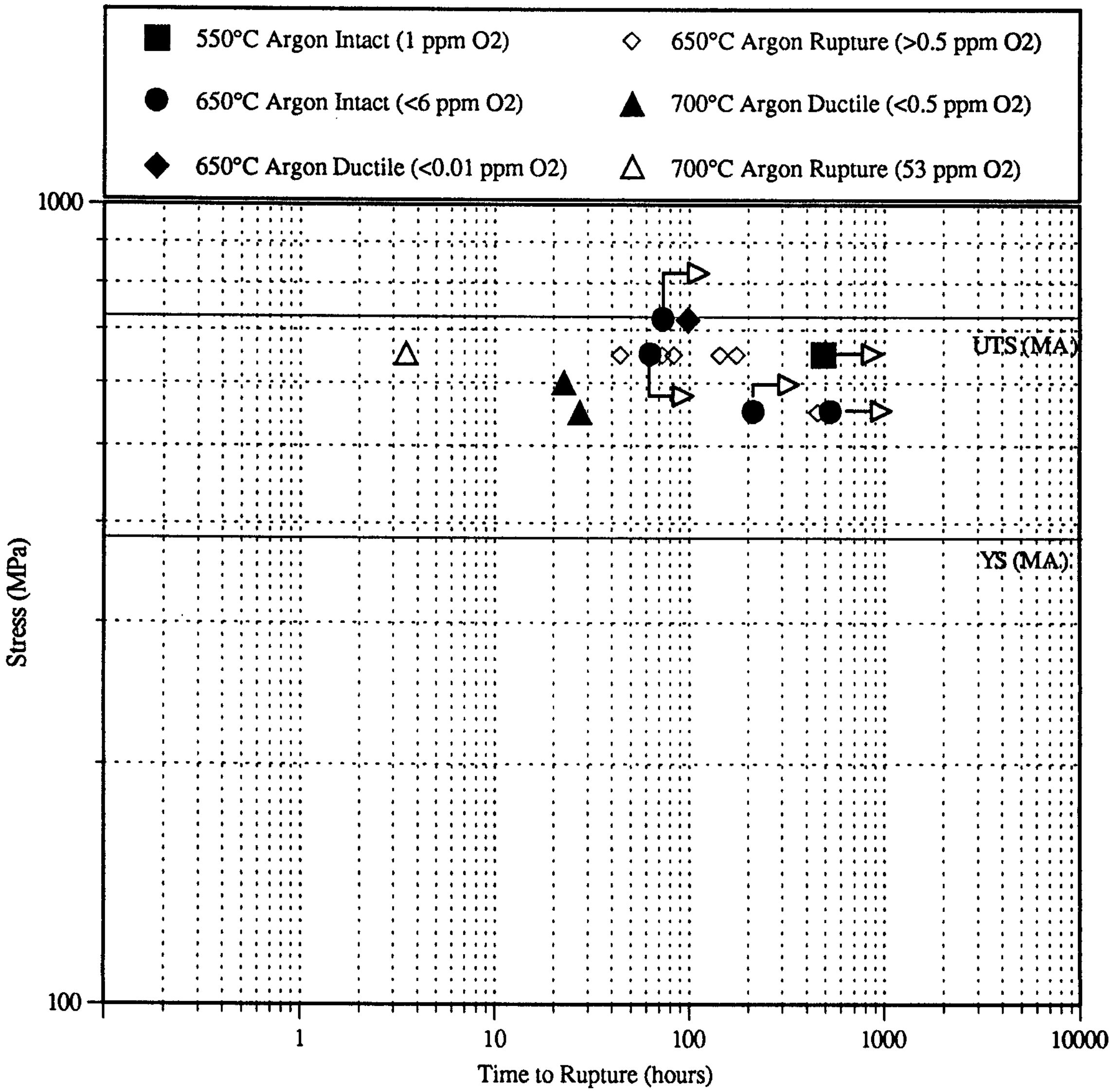

Figure 13. Stress rupture data from tests on alloy 908 performed in argon (2.5 psig, 0.172 bar gauge pressure). Arrows indicate that the test was interrupted and that the sample did not fail at the time shown. Lines are superimposed showing the tensile properties for unaged material in the mill-annealed condition (YS=389 MPa, UTS=717 MPa). Oxygen concentrations in parts per million are listed in the legend. From Morra et al. (1994).

Elastic Properties

Young's Modulus

The Young's moduli of Incoloy 908 that had been 20% cold worked and 20% cold worked followed by solution annealing have been measured ultrasonically by Ledbetter (1990). Wyrick (1992) measured the Young's modulus of annealed and aged Incoloy 908 at room temperature and above. These data suggest that the elastic moduli are higher in the aged condition, but this is a provisional interpretation because elastic property measurements by different laboratories sometimes vary by this difference (4%). Both data sets are presented in the following table and, for smaller temperature increments between 5 and 922 K, in Supplement 6.

	Young's Modulus (GPa)		
Condition:	298 K	77 K	4 K
MA, 20% CW	181	184	184
MA, 20% CW + SA (980°C/1 h)	179	182	182
Annealed + aged	188	-	-

MA = mill annealed; CW = cold worked; SA = solution annealed

On cooling to 4K, Young's modulus increases very little (<2%), in contrast with austenitic stainless steels in which the modulus typically increases about 10%.

Elastic Properties

Shear Modulus
Bulk Modulus
Poisson's Ratio

Shear modulus, bulk modulus and Poisson's ratio have been measured ultrasonically at low temperatures by Ledbetter (1990) for two conditions of Incoloy 908. These data are reported in the accompanying table and in temperature increments of 10 K in Supplement 6.

	Shear Modulus (GPa)			Bulk Modulus (GPa)			Poisson's Ratio		
Condition:	295 K	80 K	5 K	295 K	80 K	5 K	295 K	80 K	5 K
MA, 20% CW	70	71	71	146	152	153	0.293	0.298	0.299
MA, 20% CW, SA (980°C/1h)	69	70	70	147	153	154	0.297	0.302	0.303

MA = mill annealed; CW = cold worked; SA = solution annealed

The shear modulus and Poisson's ratio have very little temperature dependence (<2%) between 5 and 295 K; the bulk modulus increases less than 5% on cooling from 295 to 5 K.

Thermal Properties

Thermal Expansion

The thermal expansion of Incoloy 908 sources are as follows:

- Low temperature (4-298 K) in the annealed condition
  - Ekin (1986) National Institue of Standards and Technology (NIST)
  - Fabian and Darr (1993), Composite Technology Development (CTD)
- High temperature (298-1480 K)
  - Ekin (1986) for the annealed condition
  - Smith (1992), INCO Alloys International, Inc.
  - INCO Preliminary Data Sheet (1993) for both transverse and longitudinal directions in the aged condition.

The best fit of all data is summarized in the accompanying table. All data are included in Supplement 7.

The low temperature data of NIST and CTD differ by about 5%; this may represent material orientation effects. However, the exact condition and orientation were not reported for these measurements. The cool-down data of NIST (see Supplement 7), which differ substantially from the data taken during warm-up, are not included in the data set of the accompanying table and figure.

Temperature (K)	Thermal Expansion (%)
4	-0.174
10	-0.174
20	-0.173
50	-0.166
100	-0.145
150	-0.115
200	-0.081
250	-0.043
298	0
400	0.084
500	0.182
600	0.296
700	0.434
800	0.592
923	0.821
973	0.923
1023	1.028

Thermal Properties

Thermal Expansion

These values were calculated for specific temperatures from a fit of the combined data from Ekin (1986) (adjusted to zero at 298 K), Smith (1992), and Fabian and Darr (1993) to a sixth-order polynomial:

$$\Delta l/l = a + bT + cT^2 + dT^3 + eT^4 + fT^5 + gT^6$$

where $\Delta l/l$ is thermal expansion (%), T is temperature (K) and the values of the coefficients and estimates of their errors are presented in the following table.

	Coefficient	Standard error	*T* (coeff./err.)	95% Confidence Limits	
a	-1.74311731	0.080351462	-21.6936602	-1.90257051	-1.58366411
b	0.000143084	0.00159498	0.089708877	-0.00302207	0.003308236
c	3.5579×10^{-5}	9.965×10^{-6}	3.570421854	1.5804×10^{-5}	5.5355×10^{-5}
d	-8.511×10^{-8}	2.6429×10^{-8}	-3.22024916	-1.376×10^{-7}	-3.266×10^{-8}
e	1.1377×10^{-10}	3.361×10^{-11}	3.385112291	4.7077×10^{-11}	1.8047×10^{-10}
f	-6.707×10^{-14}	2.0284×10^{-14}	-3.30673534	-1.073×10^{-13}	-2.682×10^{-14}
g	1.4224×10^{-17}	4.6626×10^{-18}	3.050707124	4.9715×10^{-18}	2.3477×10^{-17}

At very low temperatures, the data from this best fit are about 0.02% lower than the reported low-temperature data of Fabian and Darr.

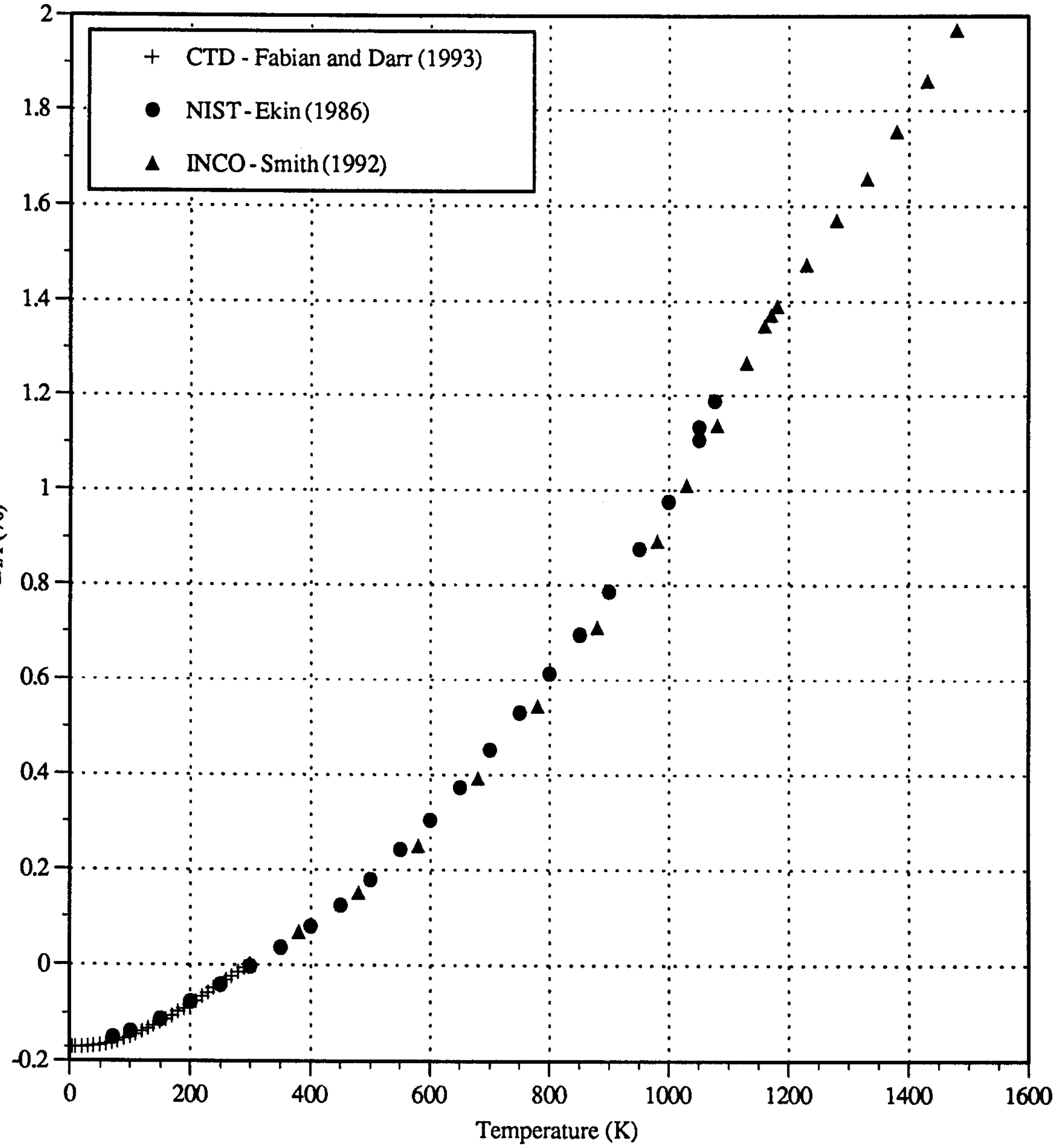

Figure 14. Linear thermal expansion (%) from 4 to 1480 K. Data from Fabian and Darr (1993), Ekin (1986), and Smith (1992).

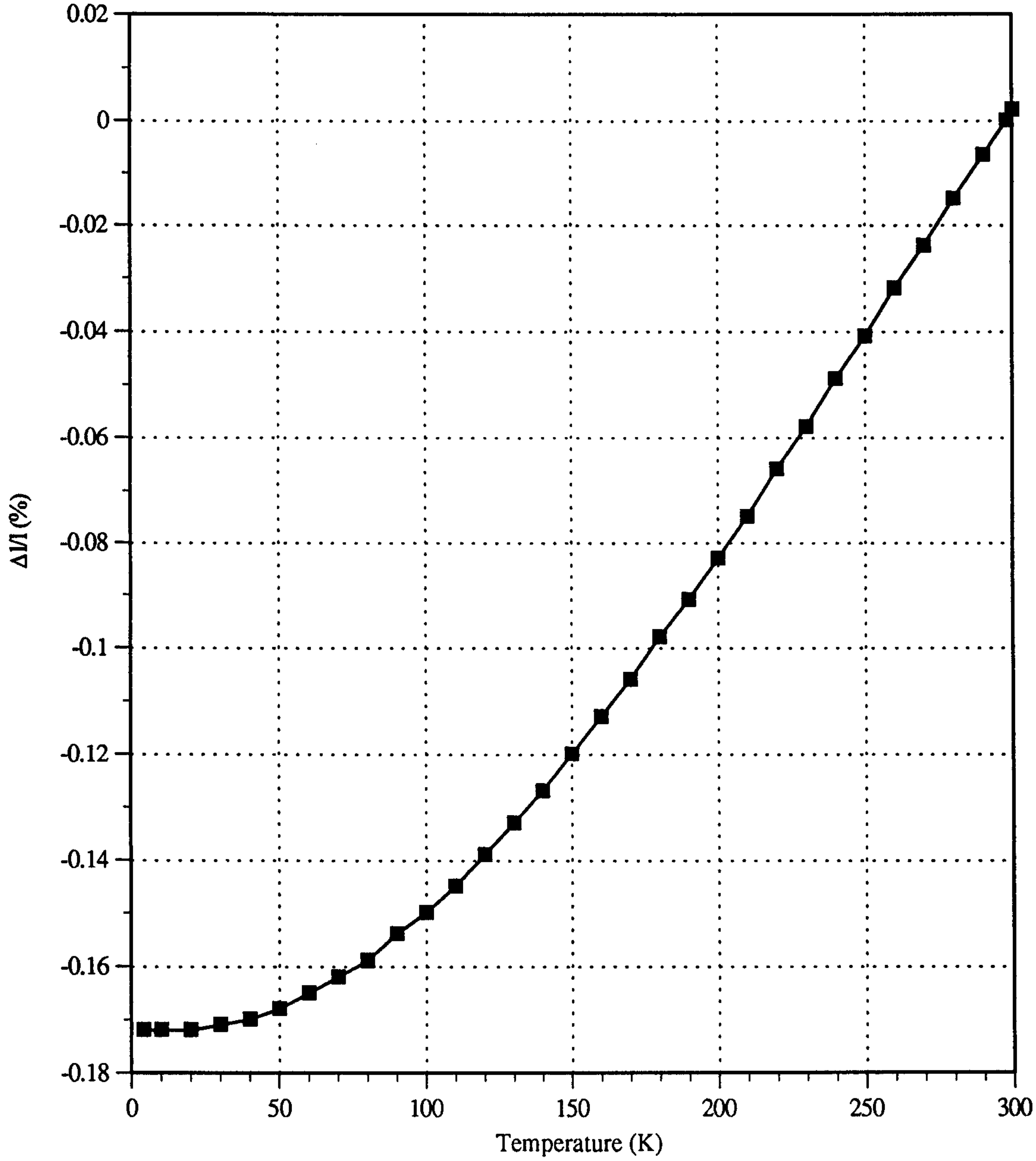

Figure 15. Low temperature linear thermal expansion (%) from 4 to 300 K. Data from Fabian and Darr (1993).

Thermal Properties

Thermal Conductivity

The thermal conductivity from 4.6 to 309 K was measured by Sparks (1993) and Smith (1993) for two conditions of Incoloy 908. The thermal conductivity at higher temperatures (298-1423 K) was reported by Weber (1993). Their data for specific temperatures are summarized in the following table, and are listed in full in Supplement 8.

	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)						
Condition	300 K	200 K	100 K	50 K	20 K	10 K	4 K
MA, SA (1050°C/1 h)	11.96	9.87	7.13	4.75	2.28	1.12	0.31
MA, SA, aged	11.66	9.51	6.64	3.94	1.65	0.71	0.10
MA, SA (1050°C/1 h), aged (650°C/200 h)	11.0	-	-	-	-	-	-

MA = mill annealed; SA = solution annealed

The Sparks data for the solution-annealed condition have been fit to the expression

$$y = a + bx + cx^2 + dx^3 + ex^4 + fx^5$$

where y is in units of $W \cdot m^{-1} \cdot K^{-1}$, x is temperature (K), and

$a = -0.27664166$
$b = 0.15258496$
$c = -0.0014040958$
$d = 8.5717171 \times 10^{-6}$
$e = -2.724432 \times 10^{-8}$
$f = 3.3775744 \times 10^{-11}$

For this fit, $r^2 = 0.9998$ and the standard error = 0.05685.

The following expression was fitted to the Sparks solution-annealed and aged condition data:

$$y = a + bx + cx^2 + dx^3 + ex^4 + fx^5$$

where y is in units of $W \cdot m^{-1} \cdot K^{-1}$, x is temperature (K), and

$a = -0.32983072$
$b = 0.1102966$
$c = -0.00063803509$
$d = 3.3300249 \times 10^{-6}$
$e = -1.1778043 \times 10^{-8}$
$f = 1.7209486 \times 10^{-11}$

For this fit, $r^2 = 0.9993$ and the standard error = 0.1184.

Thermal Properties **Thermal Conductivity**

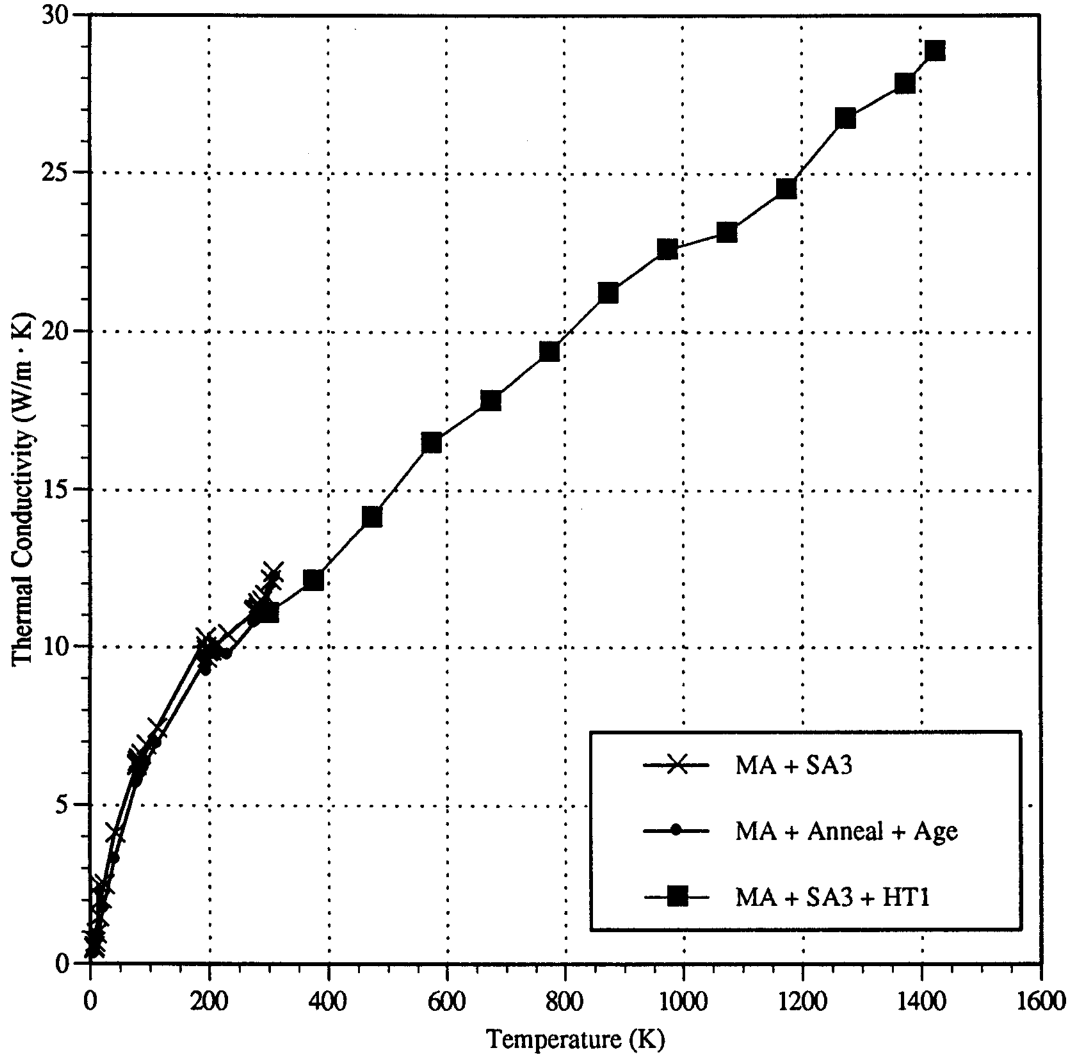

Figure 16: Thermal conductivity as a function of temperature for three processing conditions.

MA = mill annealed (980°C/1 hour)
SA3 = solution annealed (1050°C/1 hour)
HT1 = aged in vacuum (650°C/200 hours)

Thermal Properties

Specific Heat

The specific heat of various conditions of Incoloy 908 has been measured by Ho (1993) at very low temperatures (12-20 K) and by INCO (INCO Preliminary Data Sheet, 1993) at higher temperatures (291-1423 K). The low-temperature data are estimated in the accompanying table and all experimental data are summarized in Supplement 9. Logarithmic and linear plots of these data are also presented here.

	Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)			
Condition	298 K	80 K	10 K	4.2 K
MA, SA (1050°C/1 h)	-	-	1.91	0.607
MA, SA (1050°C/1 h), aged (650°C/200 h)	451	156*	2.05	0.665

MA = mill annealed; SA = solution annealed

* Estimate, based on extrapolation of high- and low-temperature data.

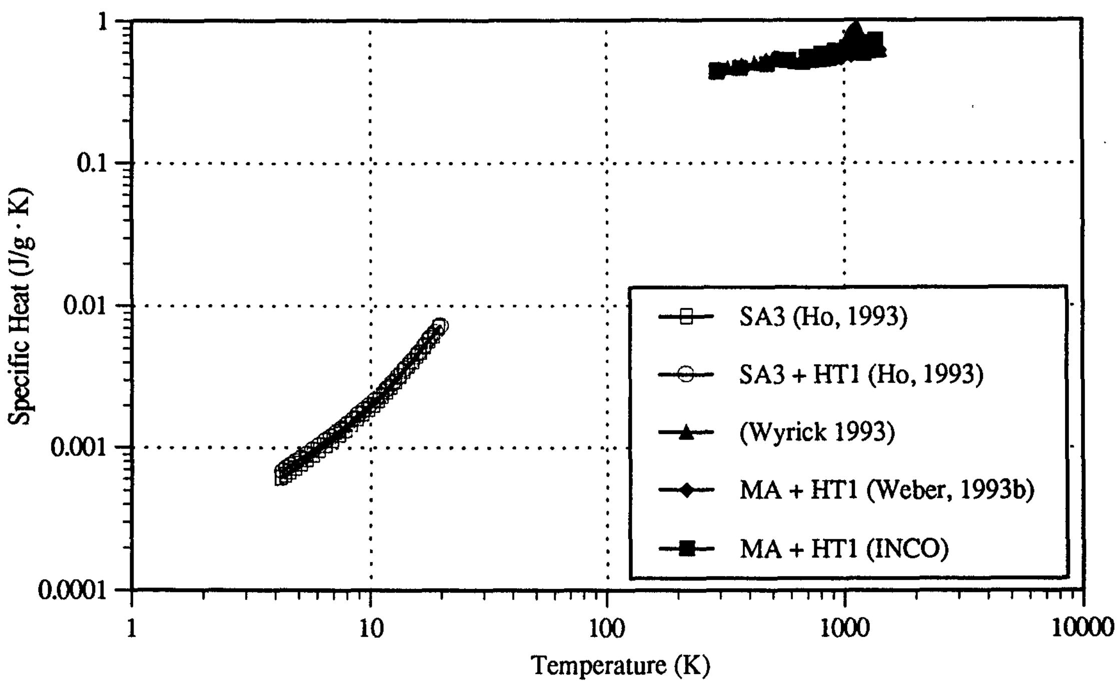

Figure 17. Logarithmic plot of specific heat at low and high temperatures.

MA = mill annealed (980°C/1 hour)
SA3 = solution annealed (1050°C/1 hour)
HT1 = aged in vacuum (650°C/200 hours)

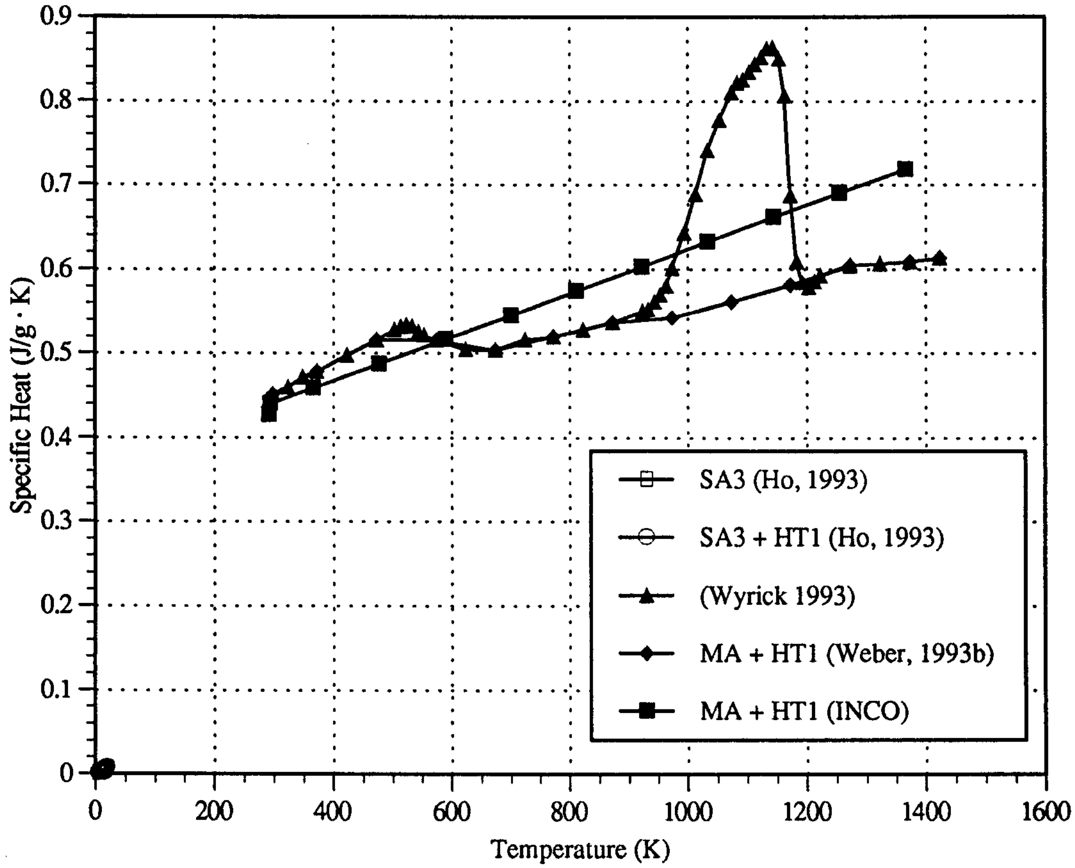

Figure 18. Linear plot of specific heat.

MA = mill annealed (980°C/1 hour)
SA3 = solution annealed (1050°C/1 hour)
HT1 = aged in vacuum (650°C/200 hours)

Magnetic Properties

Magnetization

Magnetization (*M*) versus magnetic field (*H*) curve for mill annealed condition was determined by Goldfarb (1986). This test was performed at 4 K.

Mill annealed Incoloy 908

H (kA/m)	M (kA/m)	H (kA/m)	M (kA/m)
0.002488	4.7323	-0.27341	-838.79
0.0030112	8.5779	-0.37850	-844.67
0.020346	181.33	-0.49981	-847.84
0.063305	590.41	-0.63477	-849.20
0.11897	778.17	-0.78992	-850.10
0.18782	820.24	-0.79143	-850.10
0.27625	836.08	-0.66150	-849.20
0.38139	841.96	-0.52695	-847.84
0.50281	845.58	-0.40588	-845.13
0.63791	849.20	-0.30406	-840.15
0.79306	850.10	-0.21570	-830.20
0.79453	850.10	-0.14370	-806.67
0.66456	849.65	-0.084895	-739.26
0.52990	847.39	-0.045308	-463.28
0.40828	844.22	-0.02245	-243.63
0.30649	839.24	-0.0096614	-117.54
0.21827	829.29	-0.0084639	-105.23
0.14596	802.60	-0.0032437	-52.526
0.087418	729.31	0.01980	176.72
0.047691	445.18	0.062805	582.72
0.024683	226.21	0.11840	783.14
0.015044	129.12	0.18689	821.60
0.013533	116.27	0.27559	837.43
0.0054643	34.226	0.38060	843.77
-0.017567	-195.27	0.50203	847.39
-0.060701	-601.72	0.63727	848.75
-0.11622	-786.31	0.79227	849.65
-0.18488	-823.86		

Test specimen volume: 0.227 cm^3
Hysteresis loss = 4.1 mJ / cm^3

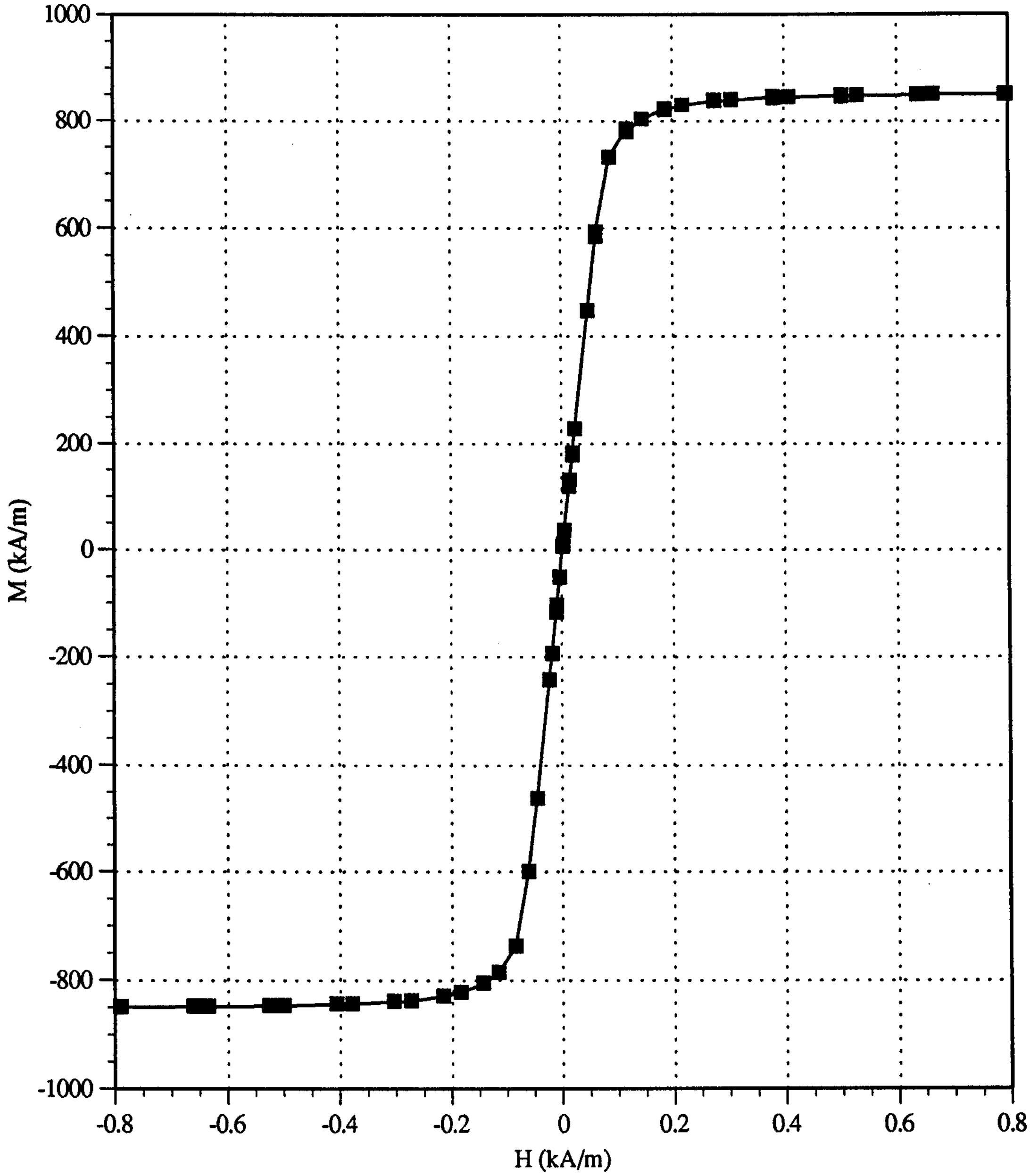

Figure 19. Magnetization as a function of magnetic field intensity at 4 K. A complete loop is shown for mill annealed alloy 908 (Goldfarb, 1986).

Magnetic Properties

Magnetization

Magnetization (*M*) versus magnetic field (*H*) curve for mill annealed plus heat treated condition was determined by Goldfarb (1986). This test was performed at 4 K.

Heat Treated 200°C / 48h + 375°C / 48h + 580°C / 96h + 700°C / 48h

H (kA/m)	M (kA/m)	H (kA/m)	M (kA/m)
0.0016858	-2.3767	-0.27297	-794.36
0.0022439	4.9270	-0.37798	-801.67
0.019869	166.28	-0.49939	-806.24
0.062933	557.15	-0.63420	-808.99
0.11861	736.31	-0.78926	-810.81
0.18718	776.99	-0.79070	-811.27
0.27593	792.53	-0.66112	-809.44
0.38085	799.84	-0.52640	-806.70
0.50224	805.33	-0.40533	-802.59
0.63719	808.07	-0.30360	-796.64
0.79212	809.90	-0.21535	-786.13
0.79353	810.36	-0.14350	-760.99
0.66387	808.53	-0.084662	-688.78
0.52919	805.79	-0.045098	-446.54
0.40798	801.22	-0.022206	-235.61
0.30629	794.82	-0.0095219	-115.63
0.21788	783.85	-0.0082547	-103.84
0.14575	758.25	-0.003081	-53.887
0.087023	682.84	0.019893	163.90
0.047365	431.23	0.062991	554.86
0.024427	218.24	0.11854	734.49
0.014765	126.79	0.18711	775.62
0.013428	114.54	0.27567	791.62
0.0051621	36.541	0.38078	801.22
-0.01773	-181.08	0.50217	805.79
-0.060631	-570.86	0.63704	808.99
-0.11622	-739.06	0.79217	810.81
-0.18486	-778.82		

Test specimen volume: 0.225 cm^3
Hysteresis loss = 4.4 mJ / cm^3

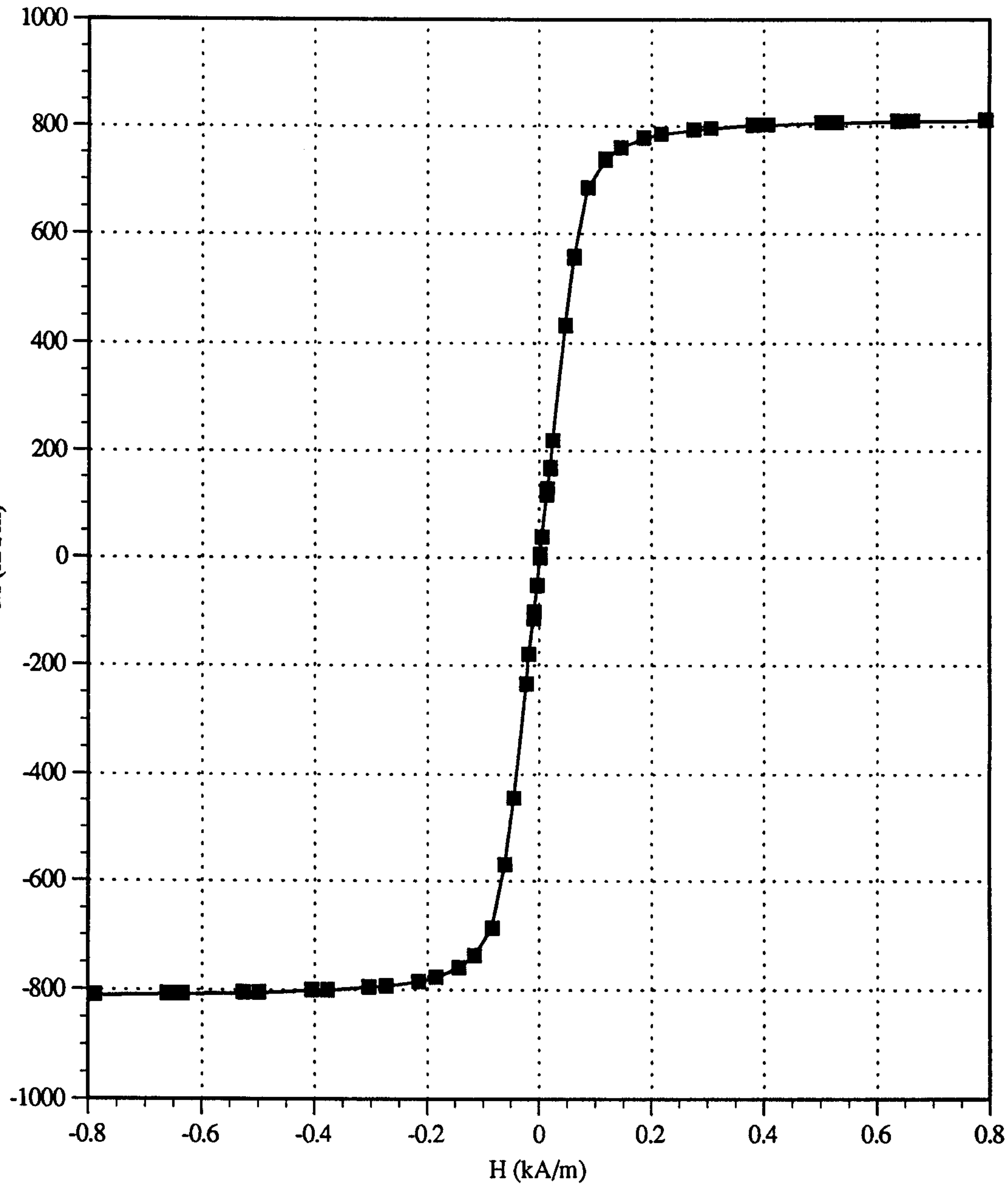

Figure 20. Magnetization as a function of magnetic field intensity at 4K. A complete loop is shown for aged alloy 908 (Goldfarb, 1986).

INCOLOY 908

SUPPLEMENTS

Supplement Definitions

Processing

Age = Precipitation hardening of the alloy by heat treatment.
AR = As-received: hot rolled and mill annealed at 980°C for one hour and air cooled.
CW = Cold Work: the percentage reduction of cross-sectional area.
FW = Flash Weld: butt welding two pieces of metal using electrical resistance heating.
Hardness = a measure of the resistance to plastic deformation.
HT = Heat treatment: aging to promote the formation of γ' strengthening phase.
Designations are as follows:
HT1 = 650°C for 200 hours in vacuum
HT2 = 650°C for 180 hours in vacuum
HT3 = 700°C for 100 hours in vacuum
HT4 = 750°C for 50 hours in vacuum
L = Longitudinal orientation: parallel to the rolling direction.
MA = Mill anneal: 980°C for one hour by INCO Alloys, and air cooled.
SA = Solution anneal: anneal at 1050°C for one hour to cause recovery, recrystallization and grain growth, creating a supersaturated solid solution.
Designations are as follows:
SA1 = 980°C for 0.5 hour in air
SA2 = 980°C for 1 hour in air
SA3 = 1050°C for 1 hour in air
SA4 = 1050°C for 5 minutes in air
T = Transverse orientation: perpendicular to the rolling direction (remaining in plane).
x% CW = x% Cold worked (reduction in thickness).

Mechanical Properties

da/dN = Crack extension per loading cycle (millimeters / cycle).

HV = Vickers microhardness: $HV = \dfrac{1854.4 \cdot P}{d^2}$

where P = indentor weight in grams
d = average length of indentation diagonals in microns
α = 136° angle between opposing faces of the diamond indentor

K = Stress intensity factor (MPa$\sqrt{\text{m}}$).
K_{min}, K_{max} = Minimum, maximum stress intensity factor.
K_{IC} = Fracture toughness: critical mode 1 stress intensity factor.
LT = Fatigue crack growth rate test crack is oriented perpendicular to the rolling direction of the plate from which it was cut and perpendicular to the plane of the plate.
Nominal grain size: ASTM E 112-88 nominal grain diameter.
P = Applied load (N)
$R = P_{min} / P_{max}$ = Load (stress) ratio.
Tensile elongation: Percentage increase in length from initial condition to failure.
TL = Fatigue crack growth rate test crack is oriented along the rolling direction of the plate from which it was cut and perpendicular to the plane of the plate.
$\Delta K = K_{max} - K_{min}$
σ_Y = Tensile yield strength (MPa): stress at 0.2% plastic strain. Yield strength approximates the transition point between elastic (linear) and plastic (nonlinear) deformation.
σ_{UTS} = Ultimate tensile strength (MPa): the maximum stress in tension.

Elastic Properties:

B = Bulk modulus (GPa): hydrostatic stress / (Δ Volume / Volume).

E = Young's modulus (GPa): ratio of tensile or compressive stress to corresponding strain below the proportional limit.

G = Shear modulus (GPa): ratio of shear stress to corresponding shear strain below the elastic limit.

Reduction of area (%): difference between the original cross-sectional area of a test specimen and the area of its smallest cross section. The reduction of area is usually expressed as a percentage of the original cross-sectional area of the specimen.

μ = Poisson's ratio: absolute value of the ratio of transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit.

Thermal Properties:

C_p = Specific Heat (J/g · K): The quantity of heat required to raise the temperature of a unit mass of a substance by a unit degree of temperature.

Thermal expansion (m/m): Δ length / initial length.

$$\alpha = \text{Linear thermal expansion coefficient (m/m/K)} = \frac{\Delta\ \text{length}}{\text{initial length} \cdot \Delta\ \text{Temperature}}$$

$$\beta = 3\alpha = \text{Volumetric thermal expansion coefficient} = \frac{\Delta\ \text{Volume}}{\text{Initial Volume} \cdot \Delta\ \text{Temperature}}$$

λ = Thermal conductivity (W/m K): Heat transfer rate across a distance and thermal gradient.

SAGBO Properties:

SAGBO = Stress-Accelerated-Grain-Boundary Oxidation: Nickel-iron superalloys suffer from oxygen embrittlement at the grain boundaries when exposed to oxygen at elevated temperatures and high tensile stresses. This issue can be avoided by reducing exposure to oxygen or by minimizing residual surface tensile stresses.

Failure type:

Ductile = failure by ductile plastic deformation (creep) with no oxygen embrittlement.

Rupture = failure by a combination of creep and SAGBO.

Electrical Properties:

Eddy current: an electric current developed in a material due to induced voltages.

W_h = Hysteresis loop loss (Joules): the energy expended in a single slow excursion around a normal hysteresis loop. The energy is the integrated area enclosed by the loop.

ρ = Electrical resistivity (Ohms): the property of a material which determines its resistance to the flow of an electric current.

$$\rho = \frac{R \cdot A}{l}$$

R = Resistance (Ω)
A = Cross-sectional area (cm^2)
l = Specimen length (cm)

χ = Magnetic susceptibility: a ratio of the induction B due to the magnetization of a material to the induction in space due to the influence of the corresponding magnetic field strength H.

$$\chi = \frac{B}{\mu_0 \cdot H} - 1 = \mu - 1$$

H = Magnetic field strength.
B = Magnetic induction (flux density).
μ_0 = Permeability of free space.
μ_r = Relative permeability: the ratio of the absolute permeability of a material to μ_0.

Supplement 1

Chemical Compositions of Alloy Heats

Chemical compositions of heats analyzed to date (wt %):

Heat designation:	Nominal	Y 9209	Y 9210	Y 9400	Y 9401K	Y 9402	HW 0530 CH 131	
Source:	INCO (1993)	INCO (1987a)	INCO (1987b)	INCO (1992)	Roberts (1992)	Hensley (1993a)	Hensley (1993b)	
Date:	-	11/1987	8/1987	5/1992	1992		4/1993	1991
Description:	-	2.3 mm strip	7 mm sheet	7 mm sheet	3.4 mm strip		extrusion billet	plate
Nickel	49	49.76	49.46	49.42	49.46	49.42	49.26	balance
Iron	balance	40.60	40.96	40.77	40.66	40.80	41.08	40.7
Chromium	4	3.83	3.86	3.99	3.97	3.99	3.96	3.98
Niobium	3	2.99	2.99	3.02	3.04	2.94	2.89	2.94
Titanium	1.5	1.58	1.57	1.57	1.50	1.55	1.57	1.74
Aluminum	1	1.04	0.97	0.98	1.02	1.03	0.95	0.93
Silicon		0.14	0.13	0.17	0.18	0.16	0.17	0.13
Manganese		0.04	0.04	0.05	0.048	0.04	0.10	0.041
Carbon		0.01	0.01	0.01	0.015	0.01	0.01	0.011
Copper		0.01	0.01	0.01	0.012	0.01	0.01	-
Molybdenum		-	-	-	0.0064	0.01	0.03	-
Cobalt		-	-	-	0.074	0.01	0.44	0.013
Tantalum		-	-	-	-	0.01	0.01	-
Phosphorus		0.002	-	0.005	0.0048	0.004	0.003	0.003
Boron		0.002	-	0.003	-	0.003	0.003	0.006
Sulfur		0.001	0.001	<0.001	0.0001	0.001	0.001	0.002
Oxygen		-	-	-	0.0057	-	-	0.0013
Nitrogen		-	-	-	0.0021	-	-	0.0020

Note: Table entries with a dash in them indicate that the element represented was not measured.

Supplement 2

Tensile Properties
Tensile Yield Strength
Tensile Ultimate Strength

Source: Hwang, et al. (1992).
Each number represents one test.

	Yield strength*			Ultimate strength		
Condition:	298 K	77 K	4 K	298 K	77 K	4 K
MA + **0%** **CW**	389	662	662	717	1082	1130
MA + **10%** **CW**						
MA + **20%** **CW**	1025	1199	1254	1135	1454	1613
MA + **0%** **CW** + SA3						
MA + **10%** **CW** + SA3						
MA + **20%** **CW** + SA3						
MA + **0%** **CW** + HT1	1034	1172	1213	1433	1626	1861
	1116	1206	1241	1433	1702	1923
MA + **10%** **CW** + HT1						
MA + **20%** **CW** + HT1	1269		1461	1482		1889
	1289		1517	1516		1917
MA + **HT1**	1034	1172	1213	1433	1626	1861
	1116	1206	1241	1433	1702	1923
MA + **HT3**	1103	1192	1227	1392	1682	1883
	1103	1192	1889	1400	1682	1883
MA + **HT4**	1034	1110	1185	1323	1585	1757
	1048	1124	1213	1365	1621	1999
MA + 20% CW + **HT1**	1269		1461	1482		1889
	1289		1517	1516		1917
MA + 20% CW + **HT3**	1227		1427	1448		1868
	1255		1441	1454		1896
MA + 20% CW + **HT4**	1248		1317	1413		1799
			1323			1799
MA + **0%** **CW** + SA3 + HT1	961		1070	1354		1780
MA + **10%** **CW** + SA3 + HT1						
MA + **20%** **CW** + SA3 + HT1	944	1070	1075	1324	1680	1776
	958		1117	1392		1782
MA + 20% CW + SA3 + **HT1**	944	1070	1075	1324	1680	1776
	958		1117	1392		1782
MA + 20% CW + SA3 + **HT3**	986	1130	1137	1365	1660	1723
	986		1165	1365		1765
MA + 20% CW + SA3 + **HT4**	807	900	965	1206	1510	1538
	835		993	1248		1620

* Defined at 0.2% offset.

Supplement 2

Tensile Properties
Tensile Yield Strength
Tensile Ultimate Strength

Source: Tobler (1993).
Each number represents one test.

	Yield strength			Ultimate strength		
Condition:	295 K	76 K	4 K	295 K	76 K	4 K
Extruded + Tube Reduced + Annealed + Cold Drawn + Hydrogen Annealed + 12% Cold Work + HT1	1020	1135	1120	1270	1540	1635
	980	1070		1250	1540	
Extruded + Tube Reduced + Annealed + Cold Drawn + Hydrogen Annealed + 14% Cold Work + HT1	990		1190	1240		1680
MA + 20% CW (3 mm plate)			1030			1280
			1040			1230
MA + 20% CW (13 mm plate)			910			1270
			930			1300
MA + 20% CW + HT2 (3 mm plate)			1470			1910
			1440			1910
			1460			1870
			1450			1880
MA + 20% CW + HT2 (13 mm plate)			1480			-
			1490			1910
			1470			1960
			1470			1890

CW = cold work
HT1 = aged 650°C for 200 hours in vacuum
HT2 = aged 650°C for 180 hours in vacuum
HT3 = aged 700°C for 100 hours in vacuum
HT4 = aged 750°C for 50 hours in vacuum
MA = mill annealed 980°C for one hour
SA3 = solution annealed 1050°C for 1 hour in air

Supplement 2

Tensile Properties
Tensile Elongation
Tensile Reduction of Area

Source: Hwang, et al. (1992).
Each number represents one test.

	Tensile Elongation (%)			Tensile R.A. (%)		
Condition:	298 K	77 K	4 K	298 K	77 K	4 K
MA + **0%** CW		59.4	36.9			
MA + **10%** CW						
MA + **20%** CW		19.1	20.6			
MA + **0%** CW + SA3						
MA + **10%** CW + SA3						
MA + **20%** CW + SA3						
MA + **0%** CW + HT1	15.7	21.4	27.1	32.9	30.7	32.9
	17.3	22.0	29.9	34.9	38.1	33.9
MA + **10%** CW + HT1						
MA + **20%** CW + HT1	17.9		23.5			
	20.1		24.5			
MA + **HT1**	15.7	21.4	27.1	32.9	30.7	32.9
	17.3	22.0	29.9	34.9	38.1	33.9
MA + **HT3**	14.7	24.0	23.7	32.9	39.1	29.6
	15.7	24.4	28.3	38.5	42.1	34.6
MA + **HT4**	16.0	25.4	25.3	38.9	41.8	33.6
	16.2	26.4	26.3	42.9	42.6	34.6
MA + 20% CW + **HT1**	17.9		23.5			
	20.1		24.5			
MA + 20% CW + **HT3**	20.0		26.6			
	22.0		27.4			
MA + 20% CW + **HT4**	17.0		25.0			
			28.0			
MA + **0%** CW + SA3 + HT1						
MA + **10%** CW + SA3 + HT1						
MA + **20%** CW + SA3 + HT1	14.8	18.0	24.0			
MA + 20% CW + SA3 + **HT1**	14.0	18.0	23.7			
	15.6		24.3			
MA + 20% CW + SA3 + **HT3**	14.8	24.0	24.0			
	14.8	24.0	24.0			
MA + 20% CW + SA3 + **HT4**	15.0	25.0	23.0			
	19.0		24.0			

Supplement 2

Tensile Properties
Tensile Elongation
Tensile Reduction of Area

Source: Tobler (1993).
Each number represents one test.

	Tensile Elongation (%)			Tensile R.A. (%)		
Condition:	295 K	76 K	4 K	295 K	76 K	4 K
Extruded + Tube Reduced + Annealed + Cold Drawn + Hydrogen Annealed + 12% Cold Work + HT1	22	25	22	38	40	28
	22	33		35	38	
Extruded + Tube Reduced + Annealed + Cold Drawn + Hydrogen Annealed + 14% Cold Work + HT1	19		26	37		32
MA + 20% CW (3 mm plate)			26			52
			22			53
MA + 20% CW (13 mm plate)			30			59
			31			58
MA + 20% CW + HT2 (3 mm plate)			17			24
			15			26
			14			28
			15			24
MA + 20% CW + HT2 (13 mm plate)			16			36
			17			39
			18			43

CW = cold work
HT1 = aged 650°C for 200 hours in vacuum
HT2 = aged 650°C for 180 hours in vacuum
HT3 = aged 700°C for 100 hours in vacuum
HT4 = aged 750°C for 50 hours in vacuum
MA = mill annealed 980°C for one hour
SA3 = solution annealed 1050°C for 1 hour in air

Supplement 3

Thermomechanical Treatment Properties
Temperature Dependence of Age Hardening Response

Heat Y 9401K
3 mm sheet, annealed 6 minutes, air cooled
Source: Roberts (1992a)

T (C)	Rockwell A
un-annealed	47.5
538	49.0
593	49.5
649	51.0
704	56.0
760	60.0
815	63.5
871	58.5
927	52.0
982	50.0
1038	47.5

Supplement 3

Thermomechanical Treatment Properties
Temperature Dependence of Age Hardening Response

Source: Roberts (1992a)
Heat: Y 9401K
Condition: 3 mm sheet, annealed 6 minutes, air cooled

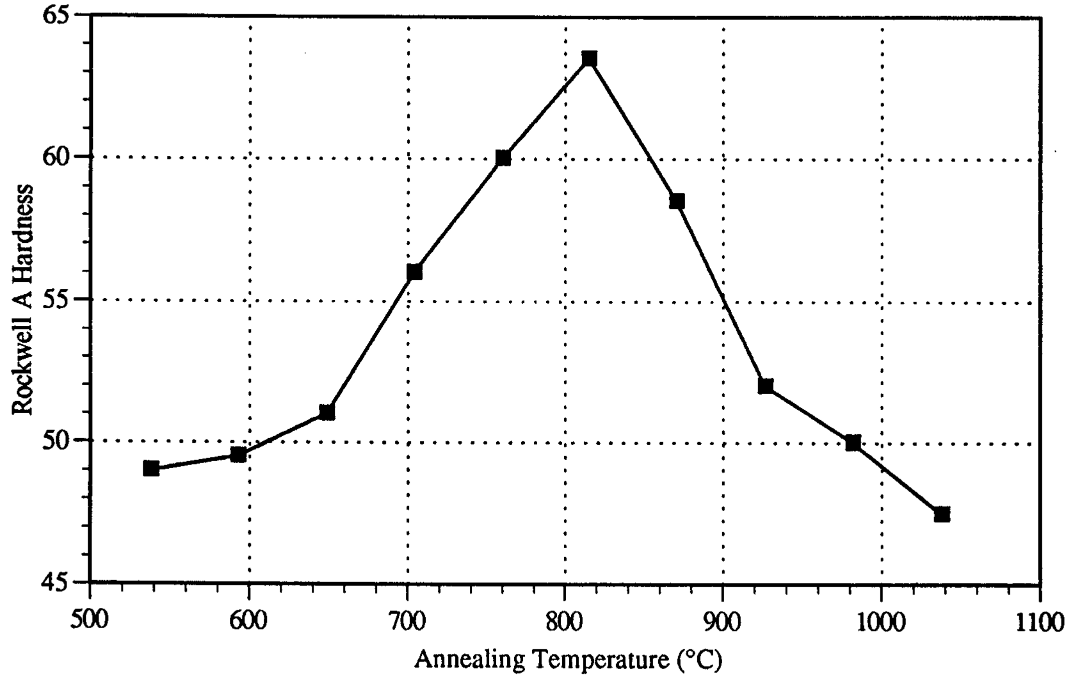

Figure S3-1. Rockwell A hardness as a function of annealing temperature.

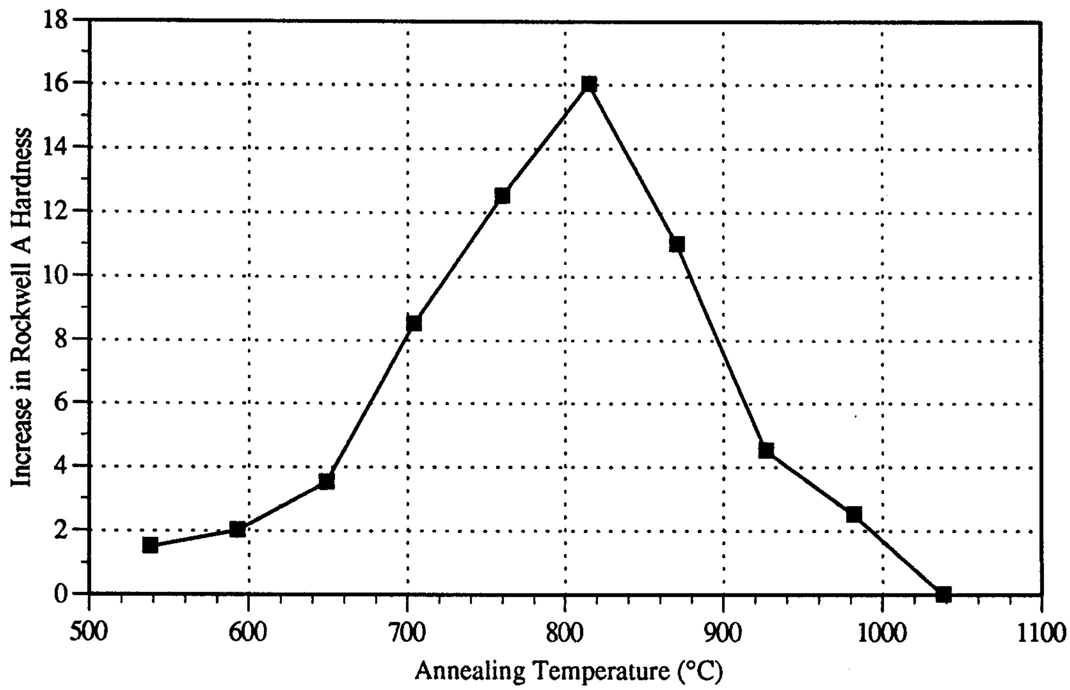

Figure S3-2. Change in Rockwell A hardness as a function of annealing temperature.

Supplement 3

Thermomechanical Treatment Properties
Post-Anneal Age Hardening Response

Source: Roberts (1992a)
Heat: Y 9401K

Annealing	Rockwell A hardness	
Temperature (°C)	Air cooled	Water quenched
982	53.5	52.0
996	53.0	49.5
1010	52.0	49.0
1038	50.5	47.5

Supplement 3

Thermomechanical Treatment Properties
Post-Anneal Age Hardening Response

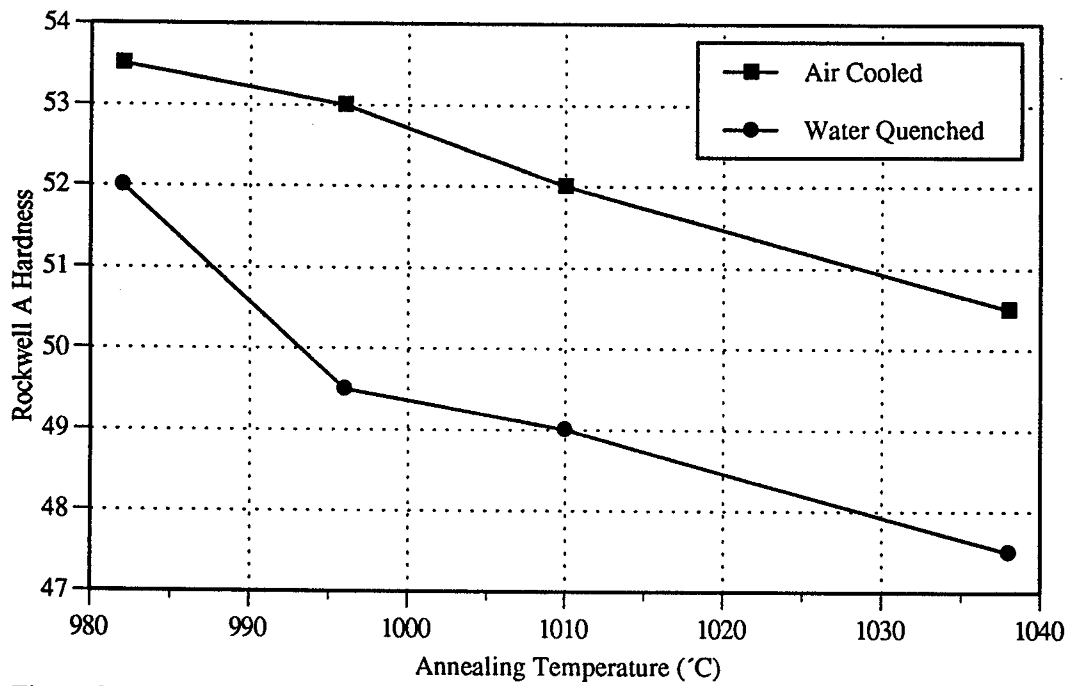

Figure S3-3. Rockwell A hardness as a function of annealing temperature with cooling method as a test parameter.

Supplement 3

Thermomechanical Treatment Properties
Post-Anneal Age Hardening Response

Source: Toma et al. (1993)
Heat: Y 9400
Vickers microhardness at 298 K (300 gram weight)

Time from 1050°C to 540°C (hh:mm:ss)		HV (kg/mm^2)
00:00:05		169
00:02:06		180
00:05:18		220
01:23:12		391
-	MA	268*
200:00:00	MA + HT1	484*

* Mill annealed (MA) + air cooled and mill annealed + 650°C / 200 hour aged (HT1) alloy 908 microhardnesses are included (in italics) for comparison.

Note: Dimensions of the specimens used were 6.4 × 9.5 × 12.7 mm.

Supplement 3

Thermomechanical Treatment Properties
Post-Anneal Age Hardening Response

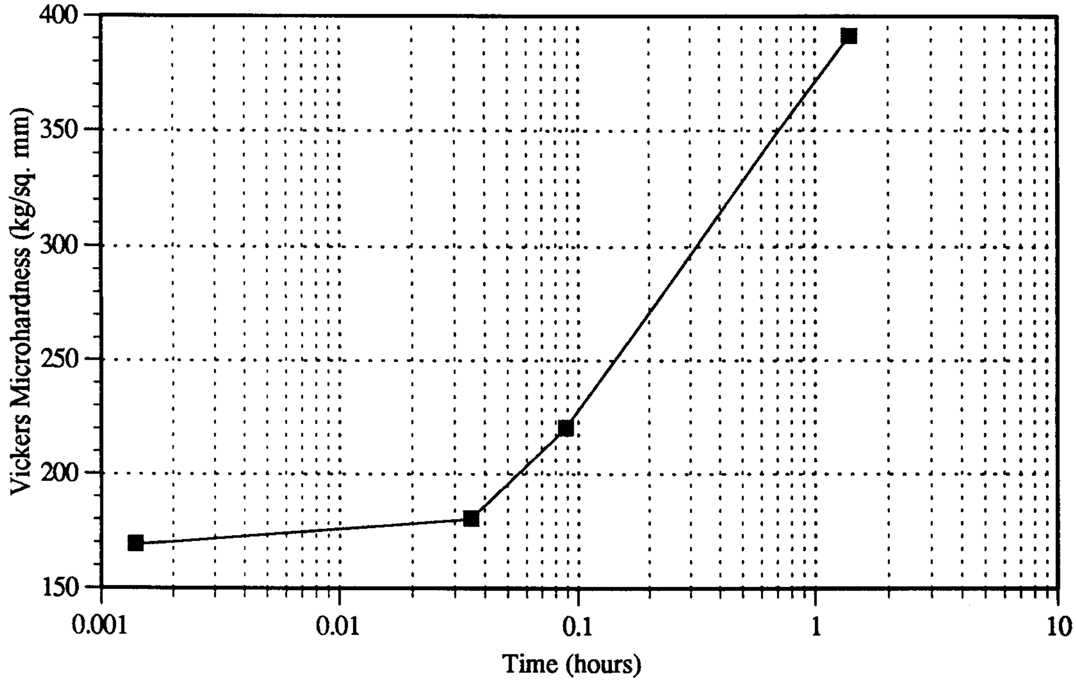

Figure S3-4. Response of Vickers microhardness to cooling rate. Hardness increases when cooling takes more than five minutes.

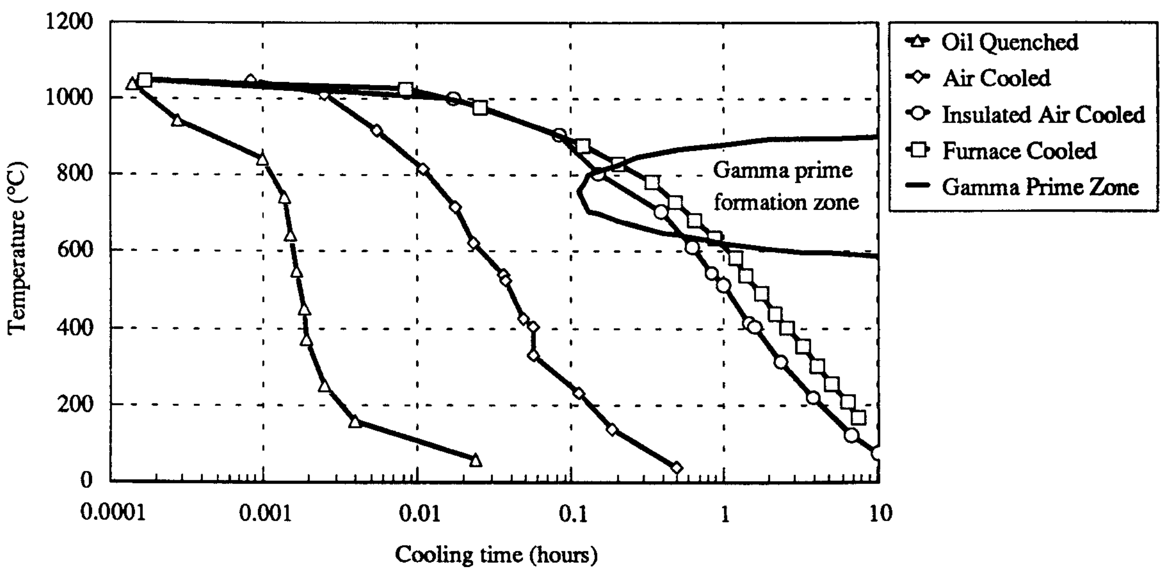

Figure S3-5. Measured cooling curves of small samples of alloy 908 with cooling method as a parameter. The γ' formation zone is superimposed to show that slow cooling will harden the alloy.

Supplement 3

Thermomechanical Treatment Properties
Work Hardening Response

Source: Roberts (1992b)
Heat: Y 9401 K
Work hardening response: Vickers microhardness at 298 K.

Condition:	HRA	HV* (kg/mm^2)
MA + SA4 + 0% CW	47.5	140
MA + SA4 + 10% CW	59	220
MA + SA4 + 20% CW	61	241
MA + SA4 + 30% CW	64	279
MA + SA4 + 40% CW	65	291
MA + SA4 + 50% CW	66	303
MA + SA4 + 60% CW	66.5	309
MA + SA4 + 70% CW	67.5	327
MA + SA4 + 80% CW	67.5	327

* Converted from Rockwell A
MA = Mill annealed 980°C for one hour
SA4 = Solution annealed 1050°C for 5 minutes

Source: Toma, et al. (1993)
Heat: Y 9400
Work hardening response and annealing recrystallization: Vickers microhardness at 298 K.

	HV (kg/mm^2)			
Condition:	L	S	T	Average
MA + 0% CW	263	270	270	268
MA + 9% CW	334	359	365	352
MA + 18% CW	362	357	405	375
MA + 0% CW + SA3	161	163	162	162
MA + 9% CW + SA3	172	169	168	170
MA + 18% CW + SA3	163	166	166	165
MA + 0% CW + HT1	481	485	485	484
MA + 9% CW + HT1	483	489	480	484
MA + 18% CW + HT1	502	508	507	506
MA + 0% CW + SA3 + HT1	407	436	463	434
MA + 9% CW + SA3 + HT1	433	485	457	458
MA + 18% CW + SA3 + HT1	422	424	445	430

L = longitudinal orientation
S = short transverse orientation
T = long transverse orientation
CW = area reduction cold work
HT1 = aged 650°C for 200 hours in vacuum
MA = mill annealed 980°C for one hour
SA3 = solution annealed 1050°C for 1 hour in air

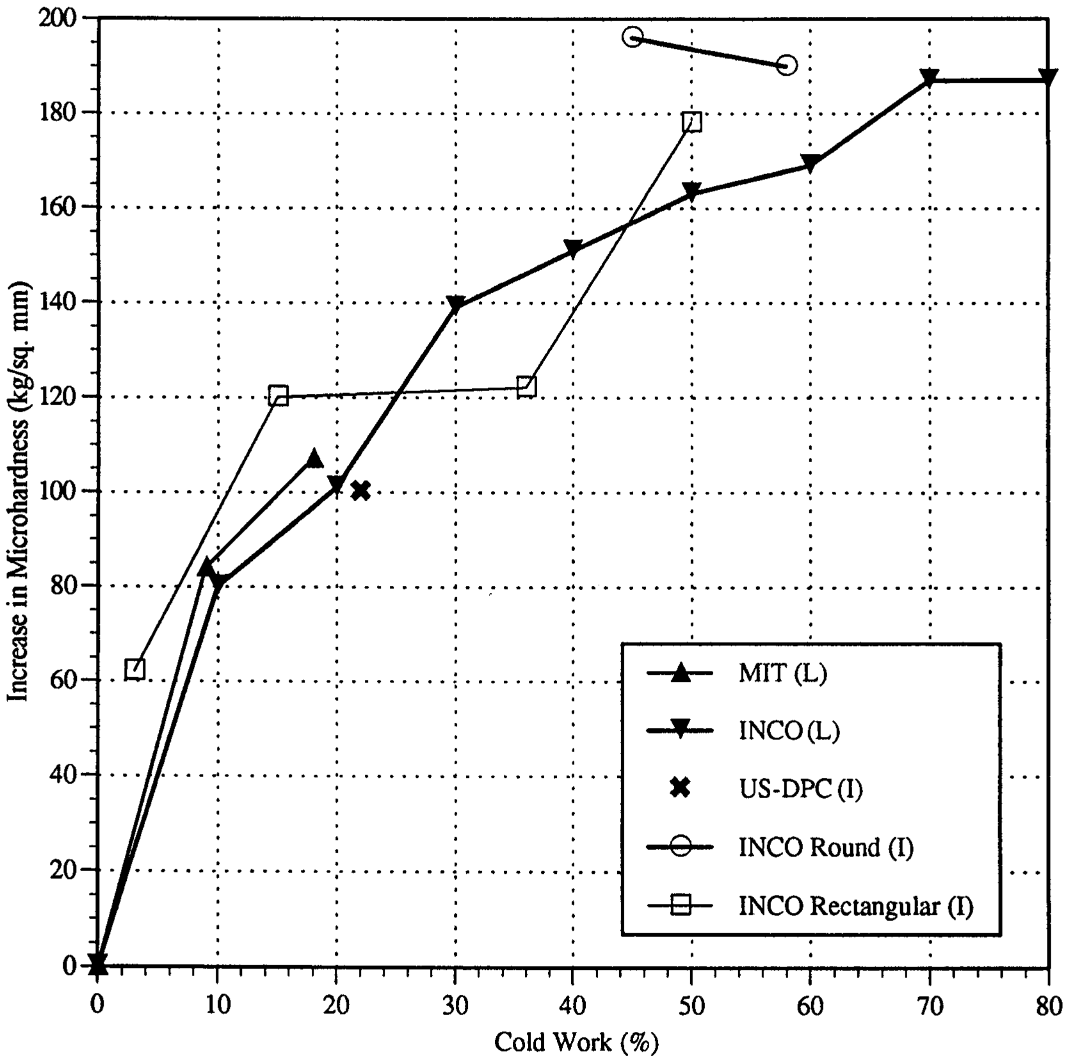

Figure S3-6. Increase in Vickers microhardness as a function of cold work, comparing laboratory results (L) with industrial results (I). All material was initially mill annealed (980°C / 1 hour) except INCO (L) which was annealed at 1050°C for five minutes (Toma et al., 1993).

Supplement 3

Thermomechanical Treatment Properties
Grain Size

Heat: Y 9400
Temperature: 298 K
Source: (Toma et al., 1993)

	Nominal grain size (μm)			
Condition:	L	S	T	Average
MA + 0% CW	21	20	22	21
MA + 9% CW	20	21	21	21
MA + 18% CW	21	25	21	22
MA + 0% CW + SA3	105	88	108	100
MA + 9% CW + SA3	99	110	105	105
MA + 18% CW + SA3	106	105	102	104
MA + 0% CW + HT1	25	24	24	25
MA + 9% CW + HT1	25	27	25	25
MA + 18% CW + HT1	28	34	29	30
MA + 0% CW + SA3 + HT1	119	79	92	91
MA + 9% CW + SA3 + HT1	111	87	104	100
MA + 18% CW + SA3 + HT1	117	134	128	128

L = longitudinal orientation
S = short transverse orientation
T = long transverse orientation
CW = area reduction cold work
HT1 = aged 650°C for 200 hours in vacuum
MA = mill annealed 980°C for one hour
SA3 = solution annealed 1050°C for 1 hour in air

Supplement 4

Gleeble Hot Ductility

Heat Y 9211K
Hot rolled round, 3/4 inch diameter
Source: Mankins (1992)

Gleeble Hot Ductility

Condition:	Temperature (K)	Tensile Strength (MPa)	Reduction in area (%)
As hot rolled	922	825	61.2
	1033	748	70.3
	1144	474	88.1
	1255	299	97.3
	1366	170	99.1
	1477	107	93.1
	1497	106	93.0
	1501	97	47.9
	1507	70	1.2
	1533	23	0.0
Hot rolled + Anneal	922	586	67.3
(982°C/1 hour) + air cool	1033	550	77.2
	1144	411	90.7
	1255	302	94.8
Hot rolled + Anneal	922	467	66.9
(1093°C/1 hour) + air cool	1033	434	73.5
	1144	370	88.1
	1255	298	93.5

Supplement 4

Gleeble Hot Ductility
Tensile Strength

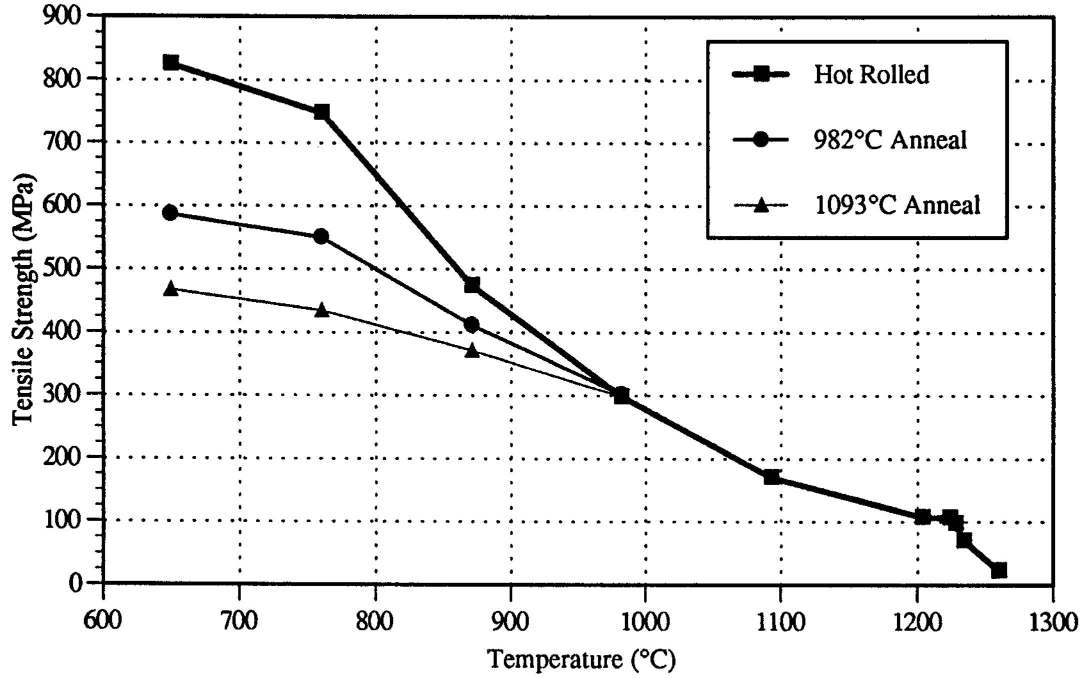

Figure S4-1. Tensile strength as a function of temperature for three processing conditions.

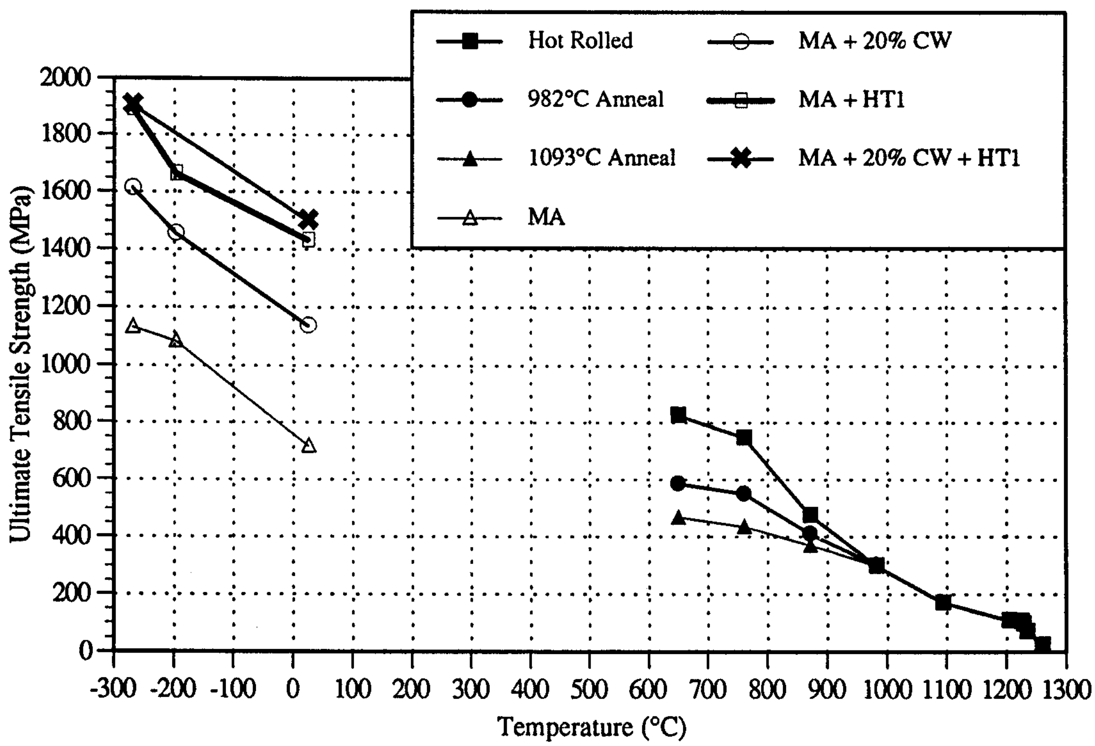

Figure S4-2. Ultimate tensile strength as a function of temperature (low temperature and Gleeble data).

Supplement 4

Gleeble Hot Ductility
Tensile Reduction of Area

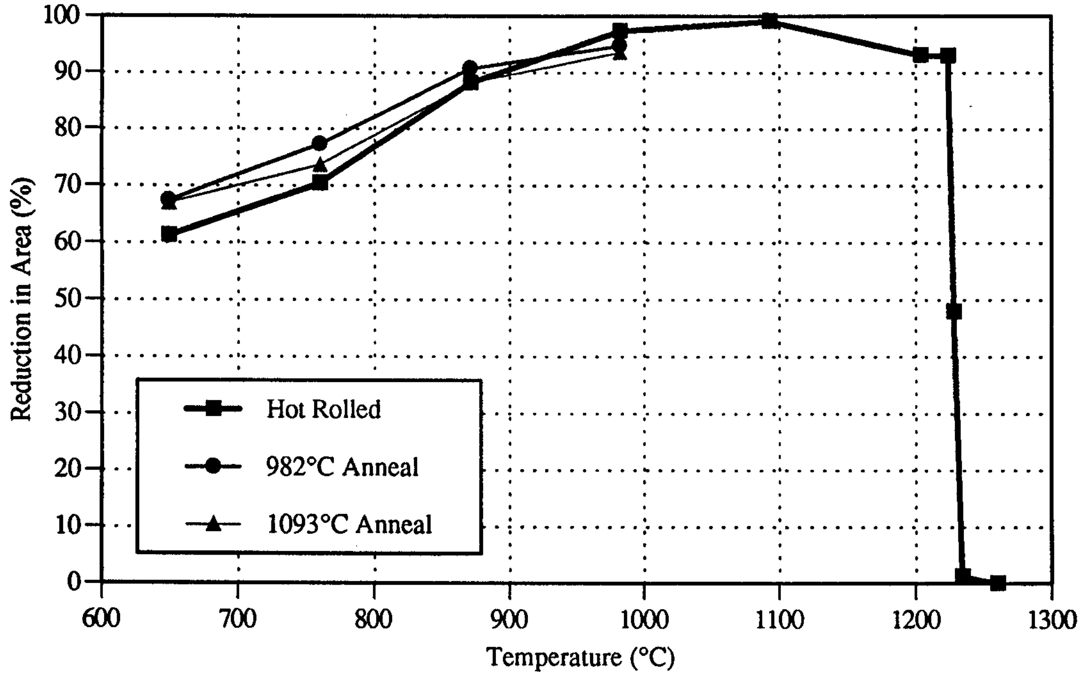

Figure S4-3. Reduction in area as a function of temperature for three processing conditions.

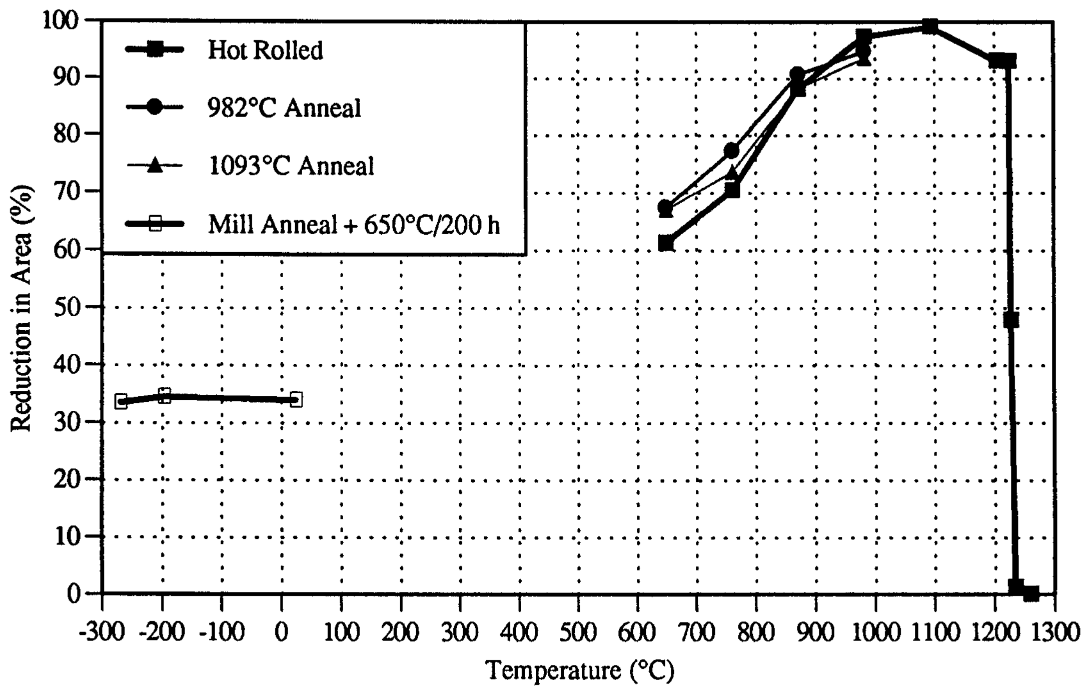

Figure S4-4. Reduction in area as a function of temperature.

Supplement 5

Fatigue Crack-Growth Rate

Source: Hwang et al. (1992)

Stress-intensity-factor change ΔK (MPa$\sqrt{m}$), and fatigue crack-growth rate da/dN (10^{-5} mm/cycle).
$R = 0.1$

Condition:	298 K		77 K		4 K	
	ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)	ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)	ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)
MA + HT1	15.0	1.42	15.0	0.268	15.0	0.812
	17.5	2.73	17.5	1.45	17.5	1.03
	20.0	4.46	20.0	2.22	20.0	1.57
	22.5	6.28	22.5	3.23	22.5	2.56
	25.0	8.49	25.0	2.95	25.0	3.39
	27.5	12.10	27.5	3.74	27.5	4.25
	30.0	16.00	30.0	4.14	30.0	5.87
			32.5	5.58	32.5	7.94
			35.0	13.20		
			37.5	16.40		
MA + HT3	15.0	2.36			15.0	0.529
	17.5	4.20			17.5	1.03
	20.0	6.38			20.0	1.92
	22.5	8.85			22.5	2.79
	25.0	11.50			25.0	4.15
	27.5	14.80			27.5	5.47
	30.0	19.10			30.0	7.18
	32.5	24.60			32.5	9.51
					35.0	11.80
					37.5	13.10
					40.0	14.20
MA + HT4	15.0	3.10			15.0	0.537
	17.5	5.30			17.0	1.04
	20.0	7.50			20.0	1.72
	22.5	10.60			22.5	2.10
	25.0	13.40			25.0	2.86
	27.5	17.10			27.5	3.98
	30.0	21.40			30.0	5.76
	32.5	27.80			32.5	7.28
	35.0	35.30				

Supplement 5 — Fatigue Crack-Growth Rate

Source: Hwang et al. (1992)

Stress-intensity-factor change ΔK (MPa$\sqrt{m}$), and fatigue crack-growth rate da/dN (10^{-5} mm/cycle). $R = 0.1$

Condition:	298 K		77 K		4 K	
	ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)	ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)	ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)
MA	15.0	0.861			15.0	0.327
+ 20% CW	17.5	1.48			17.5	1.046
+ HT1	20.0	1.54			20.0	1.40
	22.5	4.27			30.0	7.09
	25.0	5.69			35.0	12.00
	27.5	9.45			40.0	23.05
	35.0	17.40				
MA	12.0	0.70			15.0	0.842
+ 20% CW	15.0	1.61			17.5	1.12
+ HT3	17.0	2.58			20.0	1.65
	20.0	5.33			25.0	3.33
	22.0	6.60			27.5	4.82
	25.0	9.68			30.0	6.68
	27.5	12.50				
	30.0	16.70				
	33.0	19.80				
	35.0	21.80				
MA	10.0	0.497			15.0	1.04
+ 20% CW	12.0	1.53			15.0	1.30
+ HT4	15.0	2.30			17.0	1.37
	15.0	2.30			20.0	2.09
	20.0	6.10			20.0	2.10
	22.0	7.82			22.0	2.92
	23.0	8.73			25.0	4.54
	25.0	12.20			25.0	4.60
	27.5	16.10			27.5	6.66
					35.0	19.00

Supplement 5

Fatigue Crack-Growth Rate

Source: Nyilas et al. (1992)
Condition: Mill Anneal + 700°C/50 hours
Stress-intensity-factor change ΔK (MPa$\sqrt{m}$), and fatigue crack-growth rate da/dN (10^{-5} mm/cycle).
Temperature: 4 K and 20 K (Combined)

$R = 0.1$	
ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)
12.76	0.067
13.16	0.568
13.39	0.149
13.61	0.323
13.87	0.284
13.90	0.215
14.60	0.409
16.37	0.736
16.78	0.754
16.85	1.85
17.19	0.890
18.42	1.21
19.16	1.29
19.36	0.778
20.79	1.16
21.21	1.54
21.47	1.68
21.57	1.37
23.40	2.60
23.96	1.54
24.62	2.47
25.48	2.35
26.56	3.75
28.00	4.57
29.47	4.43
31.66	7.99
34.40	7.39
37.11	12.2
40.38	16.8

Supplement 5

Fatigue Crack-Growth Rate

Source: Nyilas et al. (1992)
Condition: Mill Anneal + 700°C/50 hours
Stress-intensity-factor change ΔK (MPa$\sqrt{m}$), and fatigue crack-growth rate da/dN (10^{-5} mm/cycle).
Temperature: 4 K and 20 K (Combined)

$R = 0.7$	
ΔK (MPa · $m^{1/2}$)	da/dN (10^{-5} mm/cycle)
11.61	0.178
14.34	1.70
14.48	1.53
11.74	0.722
11.93	0.931
12.14	0.730
12.19	0.618
14.19	1.33
14.62	0.994
15.06	1.27
15.26	1.25
17.24	2.69
17.40	1.52
18.08	1.67
18.70	1.68
19.31	2.12
20.01	4.10
20.30	2.88
21.23	6.35
21.49	3.23
22.48	4.04
22.92	3.15
23.21	6.00
23.29	6.88
24.18	7.45
25.15	5.54
28.50	8.08
32.28	13.52
36.69	17.79
26.20	4.42
28.81	13.20
33.17	20.70

Supplement 6

Elastic Properties
Young's Modulus, Poisson's Ratio

Sources: MA data from Ledbetter (1990); annealed + aged data from Wyrick (1992)

	Young's Modulus (GPa)			Poisson's Ratio	
Temperature (K)	MA + 20% CW + SA2	MA + 20% CW	Annealed + Aged	MA + 20% CW + SA2	MA + 20% CW
5	182.3	184.2	-	0.3029	0.2987
10	182.3	184.2	-	0.3029	0.2987
20	182.3	184.2	-	0.3030	0.2988
30	182.3	184.1	-	0.3030	0.2988
40	182.2	184.1	-	0.3028	0.2985
50	182.2	184.1	-	0.3027	0.2985
60	182.1	184.0	-	0.3027	0.2985
70	182.0	184.0	-	0.3025	0.2980
80	181.9	183.8	-	0.3023	0.2979
90	181.8	183.7	-	0.3022	0.2978
100	181.6	183.6	-	0.3019	0.2975
110	181.5	183.4	-	0.3017	0.2973
120	181.4	183.3	-	0.3014	0.2971
130	181.2	183.1	-	0.3012	0.2969
140	181.1	183.0	-	0.3011	0.2968
150	181.0	182.8	-	0.3007	0.2964
160	180.8	182.7	-	0.3003	0.2960
170	180.7	182.5	-	0.3002	0.2958
180	180.6	182.4	-	0.2999	0.2956
190	180.4	182.3	-	0.2997	0.2955
200	180.3	182.2	-	0.2995	0.2952
210	180.2	182.0	-	0.2992	0.2950
220	180.0	181.9	-	0.2991	0.2947
230	179.9	181.8	-	0.2988	0.2945
240	179.7	181.6	-	0.2985	0.2940
250	179.6	181.5	-	0.2982	0.2939
260	179.5	181.4	-	0.2979	0.2935
270	179.3	181.2	-	0.2978	0.2934
280	179.2	181.1	-	0.2975	0.2932
290	179.1	181.0	-	0.2972	0.2929
295	179.0	180.9	-	0.2971	0.2929
297.5	178.9	180.8	-	0.2970	0.2928
298	-	-	187.5	-	-
366	-	-	186.8	-	-
477	-	-	185.5	-	-
588	-	-	185.5	-	-
700	-	-	179.9	-	-
811	-	-	173.7	-	-
922	-	-	166.8	-	-

Supplement 6

Elastic Properties
Young's Modulus, Poisson's Ratio

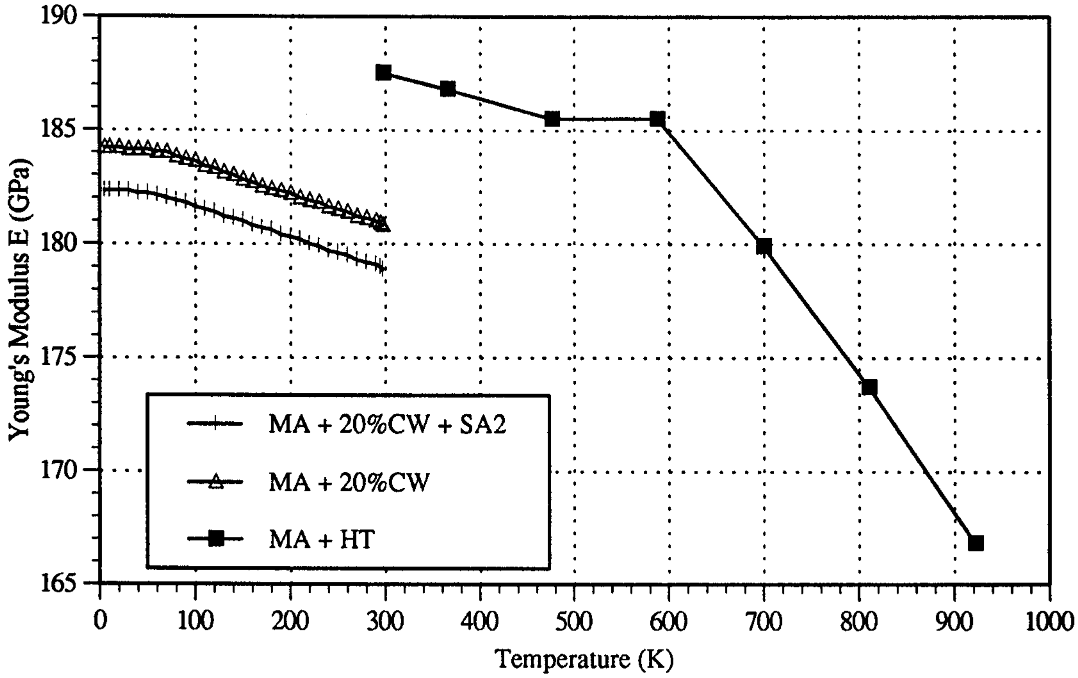

Figure S6-1. Young's modulus as a function of temperature for three conditions.

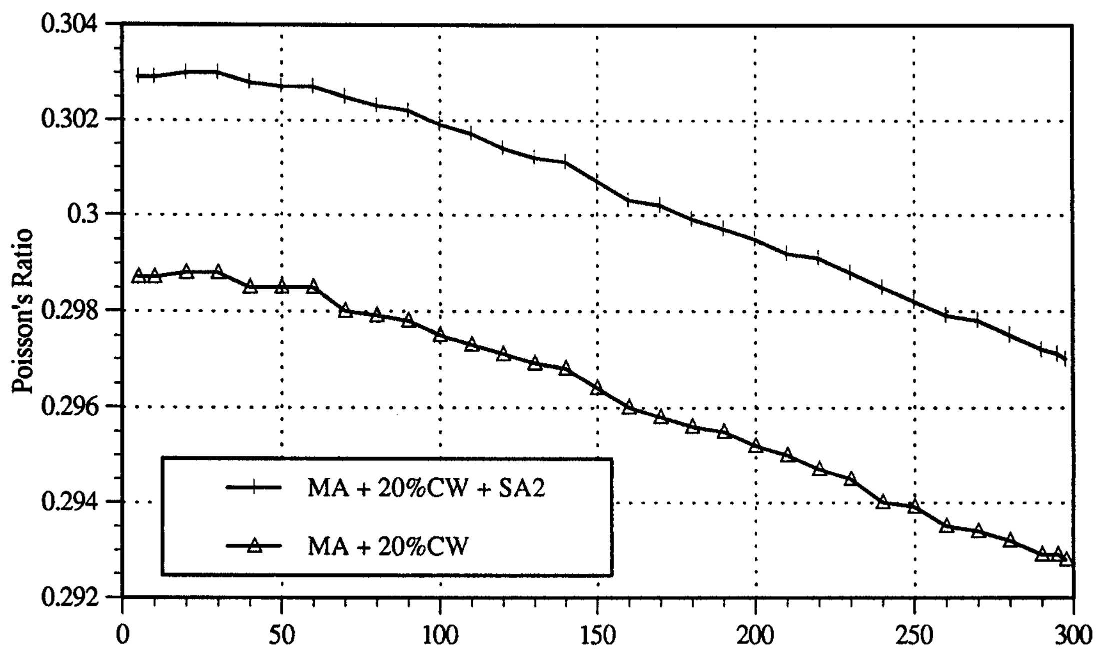

Figure S6-2. Poisson's ratio as a funtion of temperature for two conditions.

Supplement 6

Elastic Properties
Shear, Bulk Modulus

Source: Ledbetter (1990)

Temperature (K)	Shear Modulus (GPa) MA + 20% CW + SA2	Shear Modulus (GPa) MA + 20% CW	Bulk Modulus (GPa) MA + 20% CW + SA2	Bulk Modulus (GPa) MA + 20% CW
5	69.96	70.93	154.2	152.6
10	69.96	70.92	154.2	152.5
20	69.95	70.89	154.2	152.5
30	69.95	70.89	154.2	152.5
40	69.93	70.88	154.0	152.3
50	69.91	70.88	153.9	152.2
60	69.89	70.87	153.8	152.2
70	69.86	70.86	153.5	151.8
80	69.83	70.81	153.3	151.6
90	69.79	70.78	153.1	151.4
100	69.76	70.74	152.8	151.1
110	69.72	70.70	152.5	150.8
120	69.69	70.65	152.2	150.5
130	69.64	70.60	151.9	150.3
140	69.59	70.55	151.7	150.0
150	69.56	70.52	151.3	149.7
160	69.53	70.49	151.0	149.3
170	69.48	70.44	150.7	149.0
180	69.45	70.39	150.4	148.7
190	69.42	70.34	150.2	148.5
200	69.36	70.32	149.9	148.2
210	69.34	70.27	149.6	147.9
220	69.28	70.24	149.3	147.6
230	69.25	70.20	149.0	147.4
240	69.20	70.16	148.6	146.9
250	69.18	70.14	148.4	146.7
260	69.15	70.10	148.0	146.4
270	69.10	70.06	147.9	146.2
280	69.05	70.03	147.5	146.0
290	69.01	70.00	147.2	145.7
295	68.99	69.97	147.0	145.6
297.5	68.98	69.96	146.9	145.5

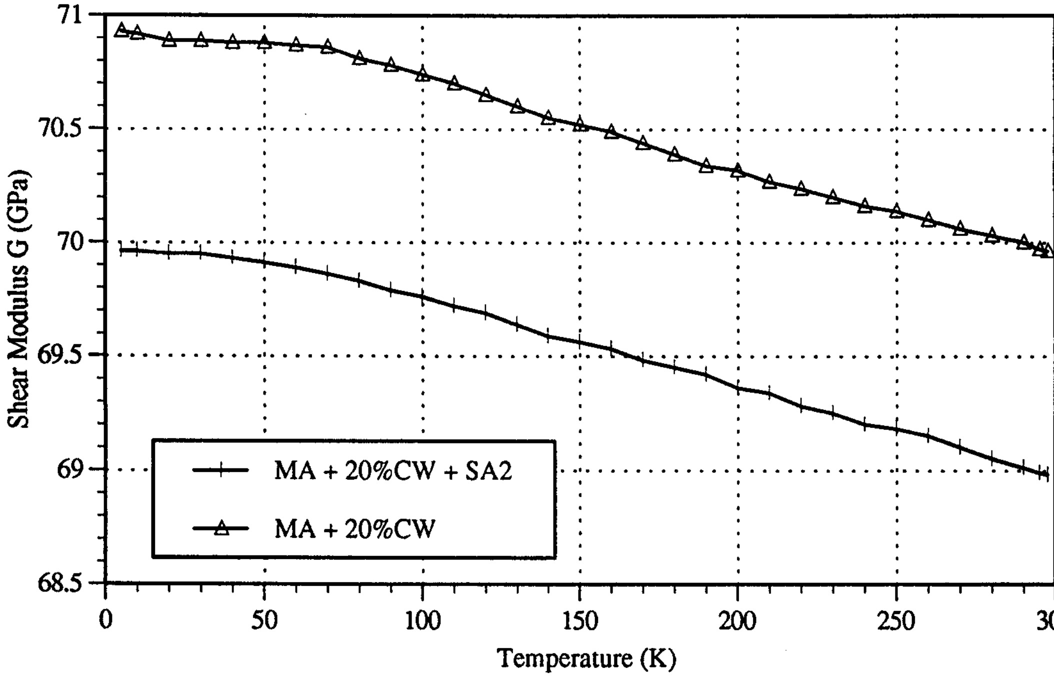

Figure S6-3. Shear modulus as a function of temperature.

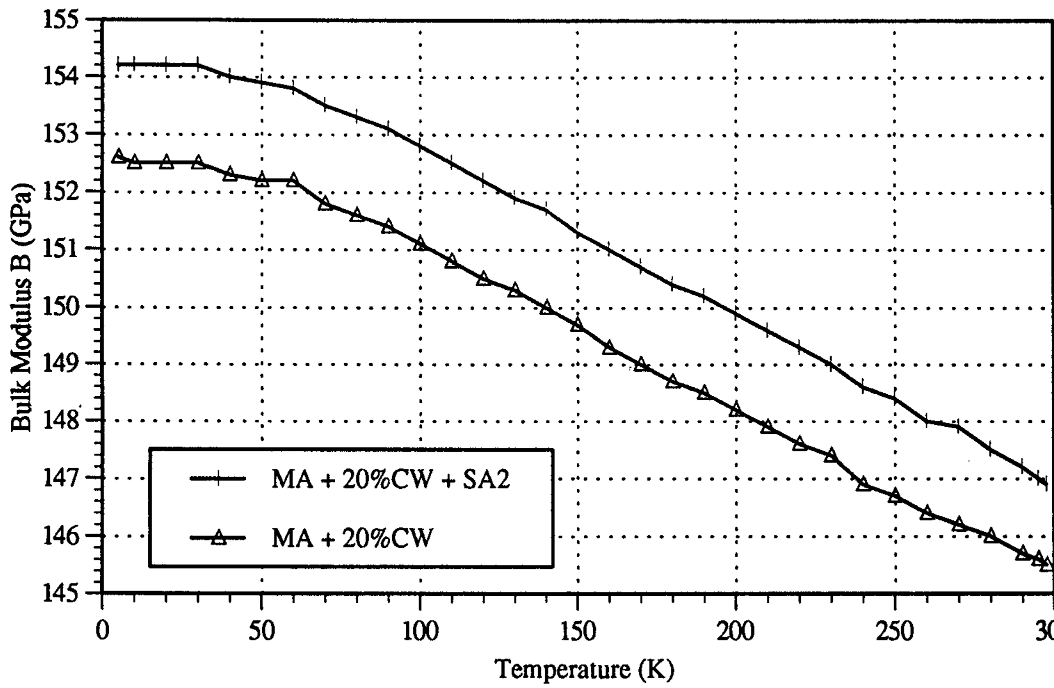

Figure S6-4. Bulk modulus as a function of temperature.

Supplement 7 — Thermal Expansion

Sources:
A - Fabian and Darr (1993)
B - Ekin (1986) [Heat HV5106]
C - Reed (1993)
D - Smith (1992)
E - INCO Preliminary Data Sheet (1993)

Temperature (K)	Thermal Expansion, $\Delta l/l$ (%)					
	A	B	C	D	E	
					Longitudinal	Transverse
			annealed		MA + lab age	MA + lab age
4	-0.172		-0.159			
10	-0.172		-0.158			
20	-0.172		-0.157			
30	-0.171					
40	-0.170					
50	-0.168		-0.150			
60	-0.165					
70	-0.162					
72		-0.151				
75			-0.144			
80	-0.159					
90	-0.154					
100	-0.150	-0.139	-0.132			
110	-0.145					
120	-0.139					
130	-0.133					
140	-0.127					
150	-0.120	-0.114	-0.106			
160	-0.113					
170	-0.106					
180	-0.098					
190	-0.091					
200	-0.083	-0.077	-0.069			
210	-0.075					
220	-0.066					
230	-0.058					
240	-0.049					
250	-0.041	-0.041	-0.032			
260	-0.032					
270	-0.024					
280	-0.015					
290	-0.0065					
293			**0.00**			
298	**0.00**			**0.00**	**0.00**	**0.00**
300	0.002	-0.004				
305		**0.00**				
350		0.035				
366					0.059	0.053
380				0.067		
400		0.079	0.089			

Temperature (K)	Thermal Expansion, $\Delta l/l$ (%) A	B	C	D	E Longitudinal	E Transverse
			annealed		MA + lab age	MA + lab age
422					0.103	0.099
450		0.124				
477					0.149	0.145
480				0.150		
500		0.177	0.188			
533					0.204	0.198
550		0.240				
580				0.250		
589					0.278	0.270
600		0.302	0.313			
644					0.360	0.349
650		0.371				
680				0.391		
700		0.450	0.459		0.446	0.436
750		0.530				
755					0.534	0.523
780				0.545		
800		0.611	0.617			
811					0.625	0.613
850		0.693				
866					0.719	0.706
880				0.710		
900		0.784	0.794			
922					0.822	0.802
950		0.876				
973			0.934		0.913	0.891
977					0.921	0.899
980				0.892		
1000		0.974				
1030				1.010		
1033					1.037	1.029
1050		1.104				
		1.131				
1076		1.186				
1080				1.136		
1130				1.269		
1160				1.347		
1170				1.370		
1180				1.389		
1230				1.475		
1280				1.568		

Supplement 7 — Thermal Expansion

Temperature (K)	Thermal Expansion, $\Delta l/l$ (%) A	B	C	D	E Longitudinal	E Transverse
			annealed		MA + lab age	MA + lab age
1330				1.657		
1380				1.757		
1430				1.862		
1480				1.971		
(cooling)						
1000		1.023				
950		0.921				
900		0.827				
850		0.738				
800		0.654				
750		0.575				
700		0.495				
650		0.420				
600		0.361				
550		0.300				
500		0.236				
450		0.183				
400		0.137				
350		0.092				

Supplement 7

Thermal Expansion

Source: INCO Preliminary Data Sheet (1993)
Condition: MA + lab age

Temperature (K)	Thermal Expansion Coefficient, α (m/m/K x 10^{-6}) Longitudinal	Transverse
366	8.59	7.78
422	8.32	7.97
477	8.32	8.08
533	8.66	8.41
589	9.56	9.29
644	10.40	10.08
700	11.11	10.85
755	11.68	11.43
811	12.20	11.95
866	12.65	12.42
922	13.18	12.87
973	13.52	13.19
977	13.55	13.23
1033	14.11	14.00

Supplement 8 — Thermal Conductivity

Heats: Y 9402 = MA + SA3
Y 9402 = MA + Annealed + Aged

Sources:

MA + SA3:	Sparks (1993)
MA + Annealed + Aged	Smith (1993)
MA + SA3 + HT1	Weber (1993)

	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)				Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)		
Temp. (K)	MA + SA3	MA + Annealed + Aged	MA + SA3 + HT1	Temp. (K)	MA + SA3	MA + Annealed + Aged	MA + SA3 + HT1
4.63	0.43			201	9.84	9.74	
5.14		0.29		211	10.0	9.73	
5.15	0.50			230	10.3	9.72	
6.17		0.37		274	11.1	10.73	
6.20	0.63			275	11.1	10.75	
8.26		0.53		278	11.1	10.79	
8.33	0.90			280	11.2		
12.6		0.90		283	11.2	10.92	
12.8	1.44			287	11.4		
13.1	2.42			292	11.6	11.29	
17.4	1.99			298			11.1
21.7		1.70		302	12.1		
22.1	2.46			306	12.3		
40.5		3.27		309		12.19	
41.0	4.08			373			12.1
76.5	6.19			473			14.1
77.1	6.22	5.65		573			16.5
78.1		5.67		673			17.8
78.2	6.32			773			19.3
80.3	6.40	5.76		873			21.2
84.6	6.56	5.94		973			22.5
93.3		6.30		1073			23.1
93.4	6.85			1173			24.5
111	7.39	6.90		1273			26.7
193	10.1	9.57		1373			27.8
194	9.77	9.20		1423			28.9
197	9.81	9.45					

HT1 = aged 650°C for 200 hours in vacuum
MA = mill annealed 980°C for one hour
SA3 = solution annealed 1050°C for 1 hour in air

Supplement 9 — Specific Heat

Heats: Y 9402 - MA + SA3
Y 9402 - MA + SA3 + HT1

Sources:
Ho (1993) — MA + SA3 and MA + SA3 + HT1
Wyrick (1993) — Condition unknown
Weber — MA + SA3 + HT1 (column 5)
INCO Preliminary Data Sheet (1993) — MA + SA3 + HT1 (column 6)

Temperature (K)	Specific Heat, Cp [J/(g·K)]				
	MA + SA3	MA + SA3 + HT1	Condition unknown	MA + SA3 + HT1	MA + SA3 + HT1
4.20	6.06×10^{-4}				
4.27		6.77×10^{-4}			
4.37	6.35×10^{-4}				
4.44		7.06×10^{-4}			
4.58	6.70×10^{-4}				
4.63		7.41×10^{-4}			
4.82	7.11×10^{-4}				
4.86		7.83×10^{-4}			
5.09	7.63×10^{-4}				
5.12		8.36×10^{-4}			
5.40	8.19×10^{-4}				
5.41		8.89×10^{-4}			
5.74	8.81×10^{-4}	9.55×10^{-4}			
6.10		1.03×10^{-3}			
6.11	9.53×10^{-4}				
6.47		1.11×10^{-3}			
6.51	1.03×10^{-3}				
6.84		1.18×10^{-3}			
6.95	1.13×10^{-3}				
7.22		1.27×10^{-3}			
7.40	1.23×10^{-3}				
7.61		1.35×10^{-3}			
7.87	1.33×10^{-3}				
8.00		1.45×10^{-3}			
8.35	1.46×10^{-3}				
8.43		1.57×10^{-3}			
8.83	1.58×10^{-3}				
8.89		1.69×10^{-3}			
9.32	1.72×10^{-3}				
9.38		1.81×10^{-3}			
9.82	1.86×10^{-3}				
9.89		1.97×10^{-3}			
10.3	1.99×10^{-3}				
10.4		2.14×10^{-3}			
10.8	2.14×10^{-3}				

Supplement 9 — Specific Heat

Temperature (K)	Specific Heat, Cp [J/(g·K)]. MA + SA3	MA + SA3 + HT1	Condition unknown	MA + SA3 + HT1	MA + SA3 + HT1
11.0		2.33×10^{-3}			
11.2	2.31×10^{-3}				
11.7	2.48×10^{-3}	2.58×10^{-3}			
12.2	2.68×10^{-3}				
12.3		2.82×10^{-3}			
12.7	2.92×10^{-3}				
13.1		3.17×10^{-3}			
13.3	3.18×10^{-3}				
13.9	3.45×10^{-3}				
14.0		3.58×10^{-3}			
14.5	3.75×10^{-3}				
15.0	4.05×10^{-3}	4.06×10^{-3}			
15.6	4.38×10^{-3}				
15.9		4.61×10^{-3}			
16.2	4.71×10^{-3}				
16.9	5.18×10^{-3}	5.19×10^{-3}			
17.6	5.68×10^{-3}				
17.8		5.81×10^{-3}			
18.4	6.17×10^{-3}				
18.7		6.48×10^{-3}			
19.3	7.00×10^{-3}				
19.7		7.17×10^{-3}			
20					
25					
50					
75					
100					
150					
200					
250					
291					0.4271
294					0.4392
298			0.451	0.4510	
323			0.459		
348			0.471		
366					0.4581
373			0.478	0.4780	
423			0.497		
473			0.515	0.5150	
477					0.4867

Supplement 9

Specific Heat

Temperature (K)	Specific Heat, Cp [J/(g·K)]				
	MA + SA3	MA + SA3 + HT1	Condition unknown	MA + SA3 + HT1	MA + SA3 + HT1
503			0.527		
513			0.531		
523			0.533		
533			0.532		
543			0.525		
553			0.521		
573			0.515	0.515	
589					0.516
623			0.504		
673			0.503	0.503	
700					0.545
723			0.515		
773			0.519	0.519	
811					0.574
823			0.527		
873			0.536	0.536	
923			0.550		0.602
933			0.552		
943			0.561		
953			0.569		
963			0.580		
973			0.601	0.542	
993			0.642		
1013			0.688		
1033			0.740		0.631
1053			0.777		
1073			0.810	0.561	
1083			0.821		
1093			0.825		
1103			0.834		
1113			0.843		
1123			0.851		
1133			0.862		
1143			0.863		0.661
1153			0.850		
1163			0.806		
1173			0.686	0.581	
1183			0.608		
1193			0.584		
1203			0.578		

Supplement 9 — Specific Heat

Temperature (K)	MA + SA3	MA + SA3 + HT1	Condition unknown	MA + SA3 + HT1	MA + SA3 + HT1
	Specific Heat, Cp [J/(g·K)]				
1213			0.585		
1223			0.592		
1255					0.689
1273			0.604	0.604	
1323			0.606		
1366					0.718
1373			0.608	0.608	
1423			0.613	0.613	

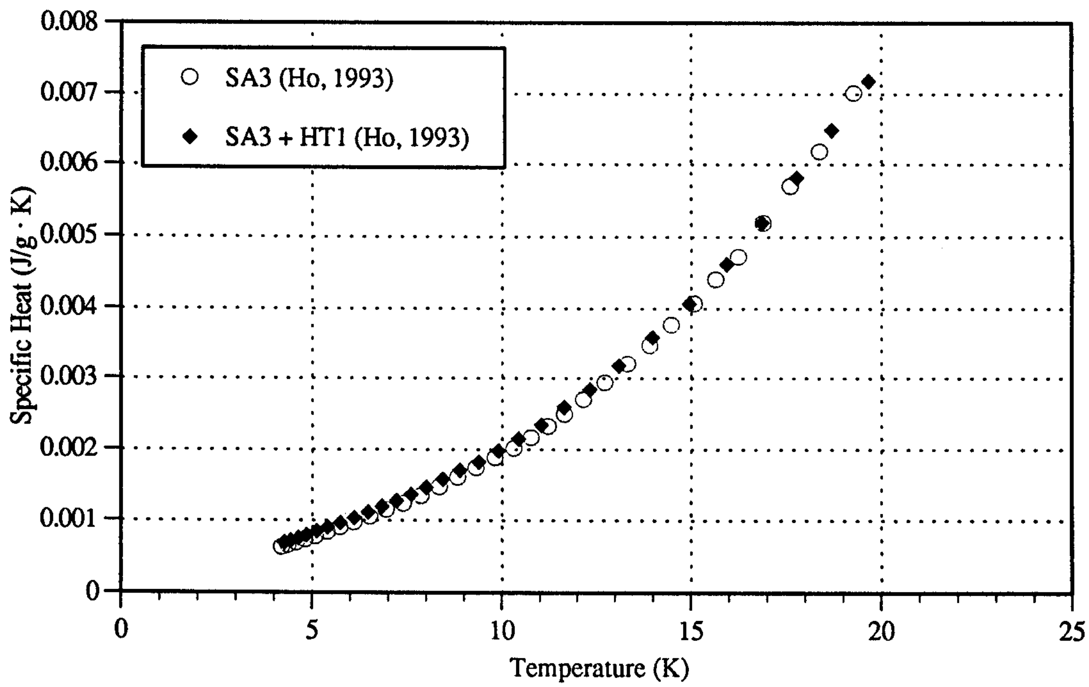

Figure S9-1. Specific heat at low temperatures.

SA3 = solution annealed (1050°C/1 hour)
HT1 = aged in vacuum (650°C/200 hours)

Supplement 10

Weld Metal Properties
Filler Metal Compositions

Source: Jang et al. (1994)

Chemical compositions of alloy 908 and weld filler metals (in weight percent).

Filler	Fe	Ni	Cr	Nb	Al	Ti	Mo	Si	C
908	41.5	49	4	3	1	1.5	-	<0.3	<0.03
9FA	40.1	50.1	4.01	3.04	1.08	1.83	0.006	<0.001	<0.001
9FC	41.7	50.2	4.03	0.99	1.00	1.84	0.009	<0.001	<0.001
9GA	41.4	50.2	4.02	1.51	1.12	1.85	0.004	<0.001	<0.001
9GB	41.0	50.3	4.03	1.50	1.07	2.32	0.005	<0.001	<0.001
9GC	40.9	50.3	4.03	1.52	1.54	1.84	0.005	<0.001	<0.001
9GD	40.5	50.3	4.00	1.48	1.59	2.31	0.002	<0.001	<0.001
9HA	41.7	51.2	4.07	0.52	1.09	1.85	0.002	<0.001	<0.001
9HB	44.6	49.7	4.03	0.50	0.55	0.57	0.002	<0.001	<0.001
9HC	40.7	50.0	4.01	0.51	1.05	1.84	1.950	<0.001	<0.001
9HD	42.9	49.4	3.99	0.50	0.57	0.58	1.970	<0.001	<0.001

Supplement 10

Weld Metal Properties
Fatigue Crack-Growth Rate

Source: Jang et al. (1994)

Fatigue Crack Growth Rate *da/dN* (mm/cycle) vs. ΔK (MPa · m½).

ΔK	*da/dN* (mm/cycle)					
(MPa · m½)	908 GTAW	9HA GTAW	9HB GTAW	9FA GTAW	9FC GTAW	9GA GTAW
20	1.15×10^{-5}	1.82×10^{-5}	2.53×10^{-5}	4.10×10^{-5}	4.51×10^{-5}	5.56×10^{-5}
		1.67×10^{-5}	1.88×10^{-5}	7.84×10^{-6}	4.56×10^{-5}	3.93×10^{-5}
		1.72×10^{-5}	2.33×10^{-5}		2.62×10^{-5}	2.91×10^{-5}
		2.53×10^{-6}	8.76×10^{-6}			
		6.85×10^{-6}	1.67×10^{-5}			
22.5	1.92×10^{-5}					
25	3.52×10^{-5}	4.85×10^{-5}	4.59×10^{-5}	2.32×10^{-5}	7.99×10^{-5}	6.41×10^{-5}
		1.69×10^{-5}	4.74×10^{-5}			
		2.22×10^{-5}				
30		1.05×10^{-4}	7.48×10^{-5}	1.26×10^{-4}	1.23×10^{-4}	1.09×10^{-4}
		8.56×10^{-5}	9.66×10^{-5}	5.58×10^{-5}	9.86×10^{-5}	9.35×10^{-5}
		7.09×10^{-5}	1.24×10^{-4}			
		4.51×10^{-5}	7.55×10^{-5}			
		6.05×10^{-5}	1.15×10^{-4}			
35		8.73×10^{-5}	1.31×10^{-4}	1.54×10^{-4}	3.58×10^{-4}	2.15×10^{-4}
		2.51×10^{-4}	1.48×10^{-4}			
40		1.25×10^{-4}	2.02×10^{-4}	2.47×10^{-4}		
		1.75×10^{-4}	2.28×10^{-4}			

Source: Jang et al. (1994)

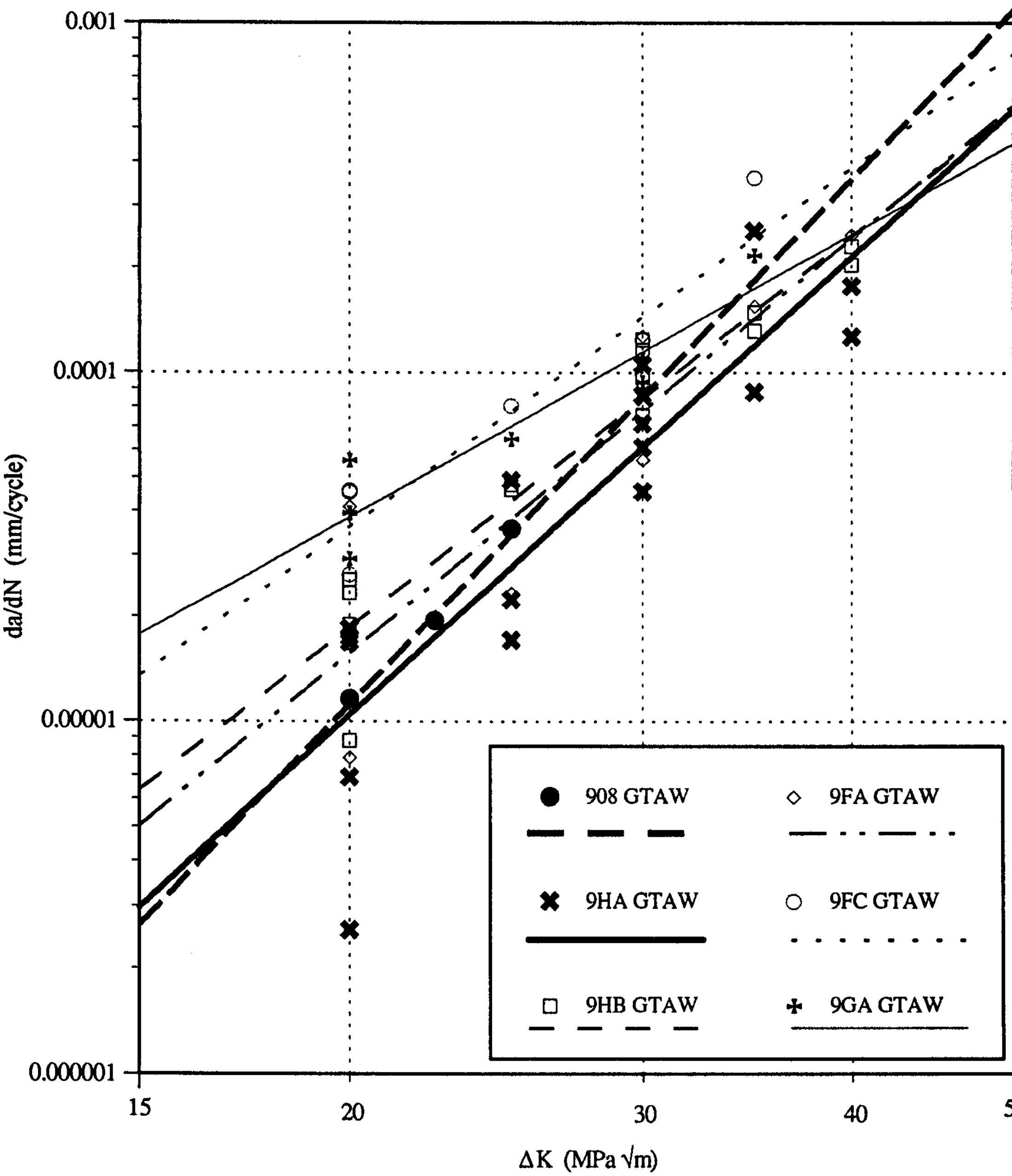

Figure S10-1. Fatigue crack growth rates at 298 K of Gas Tungsten Arc Welds aged 200 hours at 650°C.

Supplement 10

Weld Metal Properties
Fatigue Crack-Growth Rate

Source: Jang et al. (1994)

Fatigue Crack Growth Rate *da/dN* (mm/cycle) vs. ΔK (MPa · $m^{1/2}$).

ΔK	*da/dN* (mm/cycle)				
(MPa · $m^{1/2}$)	908 Base metal	908 GTAW	LBW	EBW	FW (Air)
17.5	1.61×10^{-5}				
	9.60×10^{-6}				
20	3.36×10^{-5}	1.15×10^{-5}			
	2.16×10^{-5}				
22.5		1.92×10^{-5}			
25	7.27×10^{-5}	3.52×10^{-5}	7.02×10^{-5}	1.05×10^{-4}	1.38×10^{-4}
	5.76×10^{-5}				
30	1.23×10^{-4}				
	1.01×10^{-4}				
35	1.86×10^{-4}				
	1.53×10^{-4}				
40	2.70×10^{-4}				
	2.19×10^{-4}				

Supplement 10

Weld Metal Properties
Fatigue Crack-Growth Rate

Source: Jang et al. (1994)

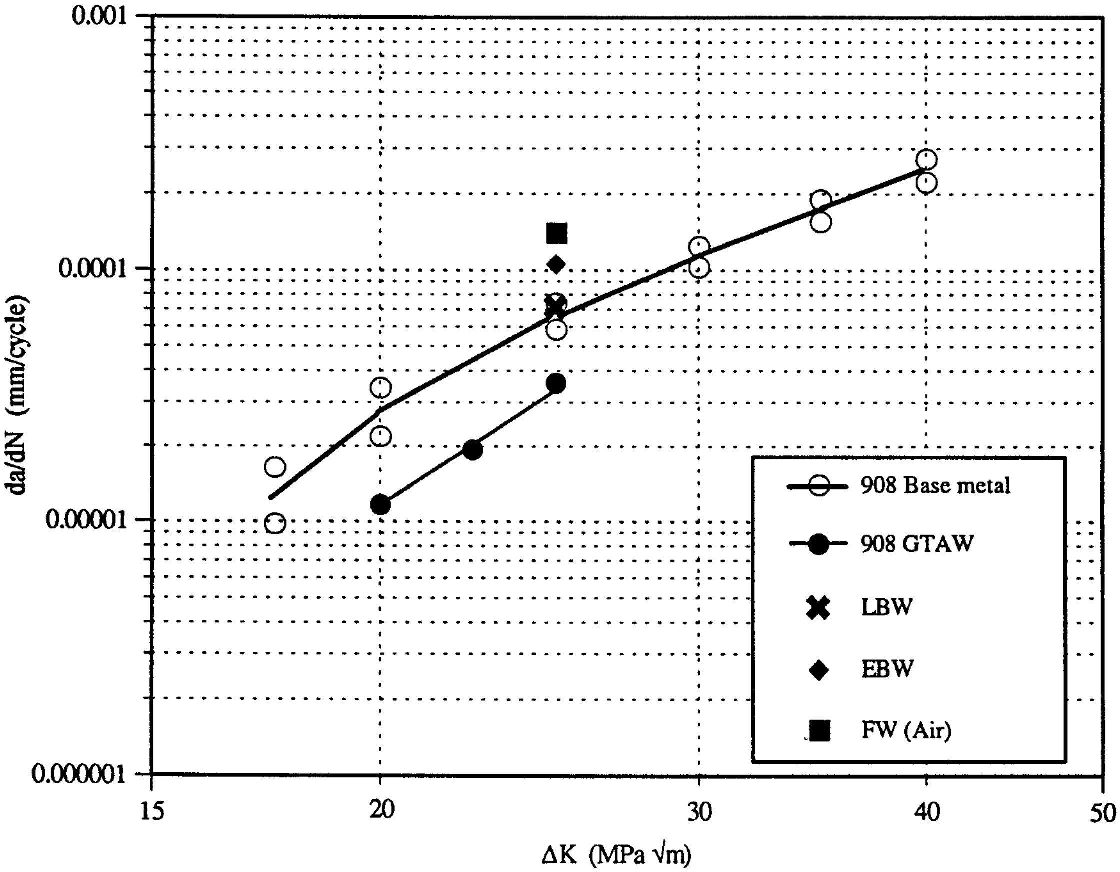

Figure S10-2. Fatigue crack growth rates at 298 K of 908 base metal, 908 GTAW, Laser Beam Weld (LBW), Electron Beam Weld (EBW), Flash Weld in air (FW), all aged 200 hours at 650°C (HT1).

Supplement 10

Weld Metal Properties
Tensile Yield Strength
Tensile Ultimate Strength
Fracture Toughness

Source: Jang et al. (1994)

Weld yield and ultimate tensile strengths and fracture toughness at 298 K.

Specimens:	Condition:	Yield Strength (MPa)	Ultimate strength (MPa)	K_{IC} ($MPa \cdot m^{1/2}$)
908 Base	MA + HT1	1075	1433	196 (±5)
908 Base	MA + 20% CW + HT1	1279	1499	-
908-GTAW	MA + HT1	1062	1316	106 (±8)
908-Electron beam weld	MA + HT1	1011	1376	126 (±18)
908-Laser beam weld	MA + HT1	1049	1358	120 (±5)
908-Flash weld in air	MA + HT1	1059	1402	86
908-Flash weld in argon	MA + HT1	1095	1429	78
9FA-GTAW	MA + HT1	1079	1347	109.5
9FC-GTAW	MA + HT1	965	1249	136 (±17)
9GA-GTAW	MA + HT1	1001	1298	133 (±8)
9GB-GTAW	MA + HT1	1035	1307	123 (±11)
9GC-GTAW	MA + HT1	1021	1276	127 (±13)
9GD-GTAW	MA + HT1	1058	1333	102 (±10)
9HA-GTAW	MA + HT1	973	1247	168 (±9)
9HB-GTAW	MA + HT1	845	1117	185 (±13)
9HC-GTAW	MA + HT1	982	1283	144 (±16)
9HD-GTAW	MA + HT1	796	1130	157 (±17)
9HA-GTAW	MA + 9% CW + HT1	1126	1307	168
9HB-GTAW	MA + 9% CW + HT1	968	1147	173 (±5)
9HD-GTAW	MA + 9% CW + HT1	896	1159	-

CW = cold work
HT1 = aged 650°C for 200 hours in vacuum
MA = mill annealed 980°C for one hour

Supplement 10

Weld Metal Properties
Tensile Yield Strength
Tensile Ultimate Strength
Fracture Toughness

Source: Jang et al. (1994)

Weld yield and ultimate tensile strengths and fracture toughness at 4 K.

Specimens:	Condition:	Yield Strength (MPa)	Ultimate strength (MPa)	K_{IC} ($MPa \cdot m^{1/2}$)
908 Base	MA + HT1	1227	1892	235 (±5)
908 Base	MA + 20% CW + HT1	1489	1903	-
908-GTAW	MA + HT1	1279	1648	105 (±1)
9HA-GTAW	MA + HT1	1074	1538	150
9HA-GTAW	MA + 9% CW + HT1	1265	1690	130 (±10)
9HB-GTAW	MA + HT1	1001	1522	214
9HB-GTAW	MA + 9% CW + HT1	1072	1505	161

CW = cold work
HT1 = aged 650°C for 200 hours in vacuum
MA = mill annealed 980°C for one hour

Supplement 10

Weld Metal Properties
Fracture Toughness - Yield Strength Relationship

Source: Jang et al. (1994)

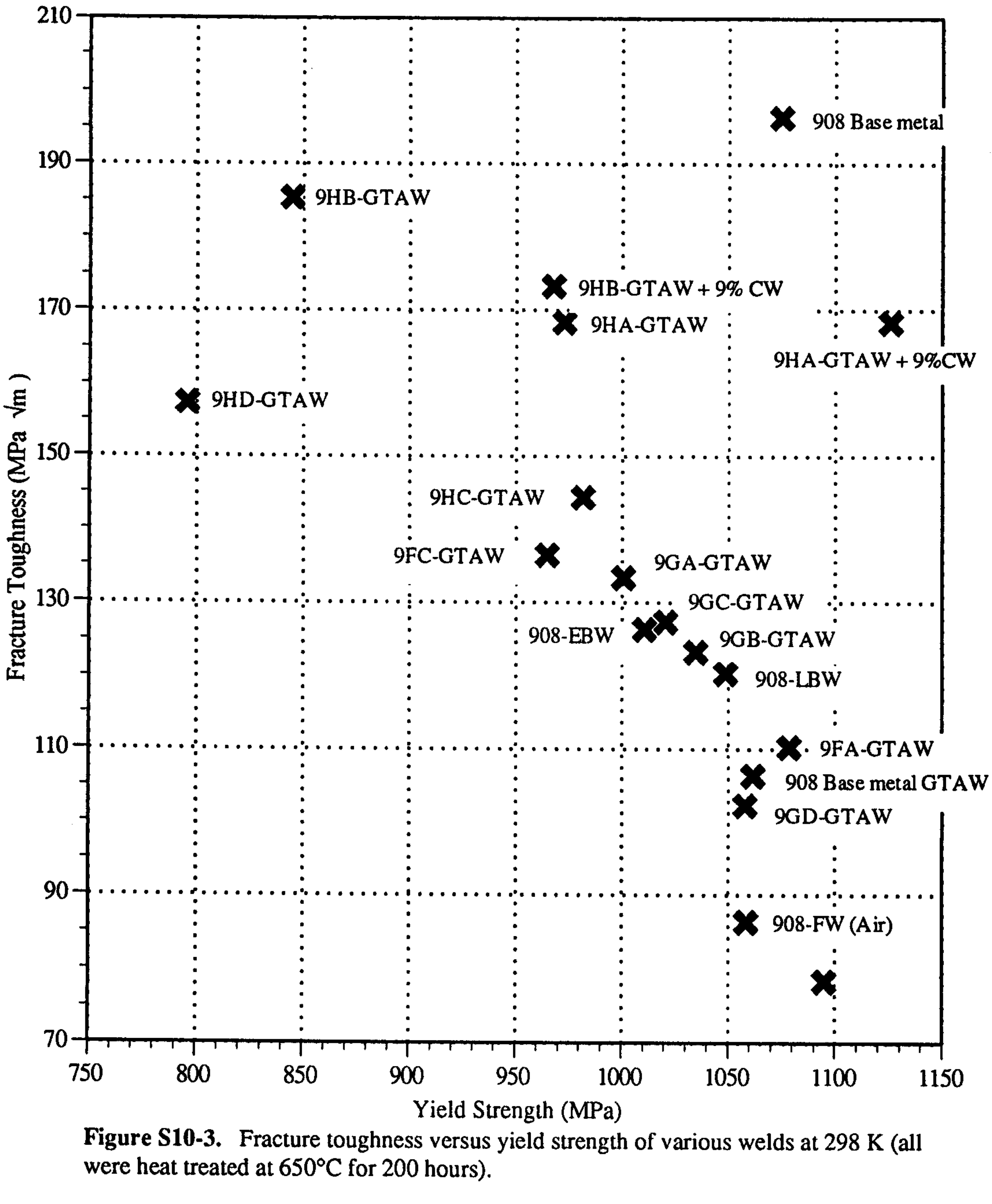

Figure S10-3. Fracture toughness versus yield strength of various welds at 298 K (all were heat treated at 650°C for 200 hours).

Supplement 10 **Weld Metal Properties**
Fracture Toughness - Yield Strength Relationship

Source: Jang et al. (1994)

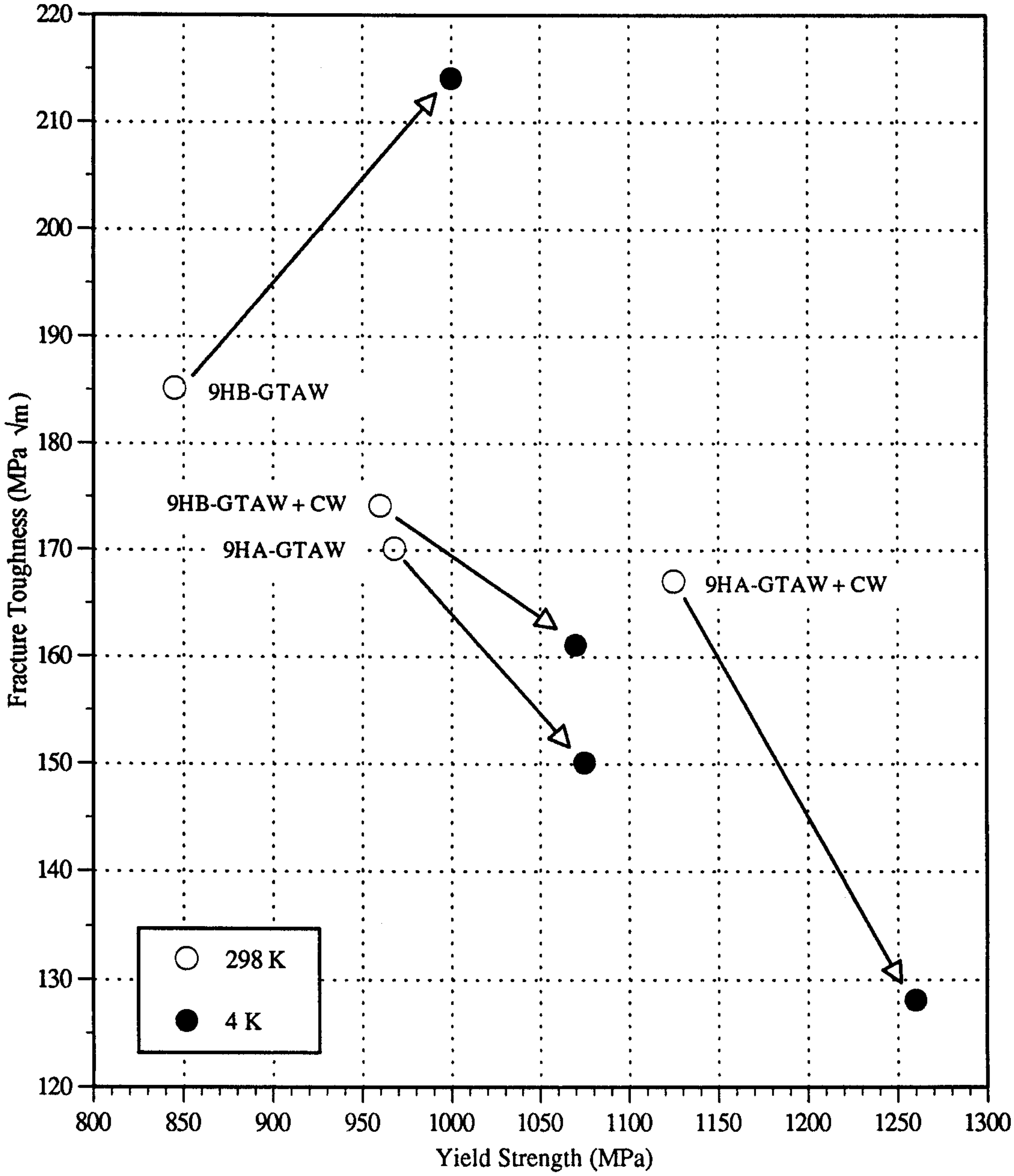

Figure S10-4. Fracture toughness versus yield strength of various welds at 298 K and 4 K (all were heat treated at 650°C for 200 hours).

Continuing Research

Research in progress

Tensile properties:
Location: MIT Plasma Fusion Center
Contact: Martin Morra
Completion date: not available
Data: Statistically significant quantities (3+) for the following conditions:
0.09" thick Incoloy 908 strip - longitudinal & transverse orientations

MA	MA + HT1
MA + 2% CW	MA + 2% CW + HT1
MA + 5% CW	MA + 5% CW + HT1
MA + 9% CW	MA + 9% CW + HT1
MA + 15% CW	MA + 15% CW + HT1
MA + 20% CW	MA + 20% CW + HT1
MA + SA3	

Tensile properties:
Location: National Institute of Standards and Technology (NIST)
Contact: Ralph Tobler
Completion date: March 1994
Data: Tensile properties for condition: Extrude + 8% CW + HT1

Tensile Properties (Effect of magnetic field)
Location: Lawrence Berkeley Laboratory (LBL)
Contact: Jin Chan
Completion date: not available
Data: Effect of high magnetic field on tensile test properties.

Fatigue crack growth rate:
Location: National Institute of Standards and Technology (NIST)
Contact: Ralph Tobler
Completion date: March 1994
Data: Fatigue crack growth rate

Stress-controlled fatigue:
Location: MIT Plasma Fusion Center
Contact: Lee Toma
Completion date: May 1994
Data: Statistically significant quantities for the following conditions:
MA + SA + 9% CW + HT1; Extruded + MA + 9% CW + HT1

Stress-controlled fatigue:
Location: National Institute of Standards and Technology (NIST)
Contact: Ralph Tobler
Completion date: March 1994
Data: Tensile fatigue testing with surface flaws to determine crack growth:
Extruded + MA + 8% CW + HT1 conduit.

Continuing Research

Research in progress

Strain-controlled fatigue:
Location: MIT Plasma Fusion Center
Contact: Lee Toma
Completion date: May 1994
Data: Statistically significant quantities for the following conditions:
MA + SA3 + 9% CW + HT1; Extruded + SA3 + 9% CW + HT1

Strain-controlled fatigue:
Location: National Institute of Standards and Technology (NIST)
Contact: Ralph Tobler
Completion date: March 1994
Data: Bending fatigue testing with surface flaws to determine crack growth:
Extruded + 8% CW + HT1 conduit.

Age hardening response:
Location: MIT Plasma Fusion Center
Contact: Martin Morra
Completion date: ongoing
Data: Hardness as a function of aging time - this project will occur in concert with the stress-rupture test program in progress at the MIT PFC.

Stress-rupture properties (SAGBO):
Location: MIT Plasma Fusion Center
Contact: Martin Morra
Completion date: ongoing
Data: Determination of a temperature / time / stress / oxygen content threshold for SAGBO failure.

Stress-rupture properties (SAGBO):
Location: MIT Plasma Fusion Center
Contact: Martin Morra
Completion date: ongoing
Data: C-ring stress-rupture testing.
Effects of shot peening, springback on stress-rupture properties.

INCOLOY 908

Continuing Research

Thermal expansion coefficient (effect of magnetic field)

Thermal expansion coefficient (effect of cold work)

Electrical resistivity

Electrical resistivity (effect of cold work)

Magnetic susceptibility

Eddy current losses

Research remaining to be done

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