EFFECTS OF NEUTRON RADIATION ON THE FATIGUE AND CREEP/FATIGUE BEHAVIOR OF TYPE 308 STAINLESS STEEL WELD METAL AT ELEVATED TEMPERATURES*

G. E. Korth and M. D. Harper

*Submitted for presentation at the Seventh ASTM International Symposium on Effects of Radiation on Structural Materials, Gatlinburg, Tennessee, June 11-13, 1974.

Prepared under auspices of U. S. Atomic Energy Commission, Idaho Operations Office under Contract No. AT(10-1)-1375.

EFFECTS OF NEUTRON RADIATION ON THE FATIGUE AND CREEP/FATIGUE BEHAVIOR OF TYPE 308 STAINLESS STEEL WELD METAL AT ELEVATED TEMPERATURES

G. E. Korth[1] and M. D. Harper[2]

ABSTRACT: Results from elevated temperature, strain controlled fatigue tests with and without hold periods at peak strain on specimens cut from Type 304 stainless steel plates welded using Type 308 stainless weld wire with controlled residual elements (CRE) are reported. Specimens were irradiated to fluences of 0.1 to 1.1×10^{22} n/cm^2, E>0.1 MeV at 450 and 600 C, while the post-irradiation test temperature was 482 and 593 C (900 and 1100 F). Irradiation reduced the fatigue life of the weld metal at 593 C by about one-half in the low cycle region (<5000 cycles to fail), but cyclic life was equivalent or slightly superior to the unirradiated material in the higher cycle region (>10,000 cycles to fail). At 482 C and at the lower fluence, the fatigue behavior of the irradiated specimens was about equivalent in the low cycle region and superior in the high cycle region. Introducing tensile hold periods at the peak strain of each fatigue cycle of the 593 C tests resulted in reductions in the fatigue life but at a much lesser rate than the base (parent) metal. Irradiation further reduced the life of the hold time tests. Hold periods had no

[1]Associate Scientist, Materials Research, Aerojet Nuclear Co., Idaho Falls, Idaho 83401

[2]Engineering Aide, Materials Research, Aerojet Nuclear Co., Idaho Falls, Idaho 83401

significant effect at 482 C. Orientation effects were seen in all weld metal tests with the parallel orientation (specimen axis parallel to the weld seam) showing a superiority in cyclic life over those taken transverse to the welding direction.

KEY WORDS: stainless steels, weld metal, radiation effects, elevated temperature, fatigue (materials), creep/fatigue interaction, cumulative damage.

The cyclic behavior of weldments subject to elastic and inelastic loading at elevated temperatures is a materials problem of considerable importance to the nuclear industry. This problem is particularly related to the development of the liquid metal fast breeder reactors (LMFBR) since welded components will be required to function for prolonged periods of time at elevated temperatures and some in a radiation environment as well. Because of the complex nature of weldments, such as weld process, solidification substructure variations, defects and residual stresses, design practice has limited the allowable strain in weld metal to one-half the values permitted in the base metal[1]. Neutron radiation further complicates the problem due to the probability of different interactions with the various species of substructure within the weldment. The object of this work was to investigate the effects of neutron radiation on the low cycle fatigue properties and creep/fatigue interactions of Type 308 weld metal with controlled residual elements (CRE) at elevated Temperatures and to compare them with the base metal.

PROCEDURE

Strain-controlled fully reversed uniaxial fatigue tests were conducted using uniform gage specimens cut from various orientations and positions within a weldment. Details of the specimens and their relative orientation and position with respect to weld seam are shown in Fig. 1. Test set up details can be found elsewhere[2,3]. Specimens were fatigued to failure at constant strain ranges from approximately 0.35 to 2.0 per cent peak-to-peak, and the strain rate was controlled at $4x10^{-3}s^{-1}$. Strain on the weld metal specimens was measured by a direct reading axial extensometer with ceramic knife blades positioned at 9.52 mm (0.375 inch) on the uniform gage section of the specimen. Some of the base metal specimens were hourglass-shaped and the strain signal for these specimens was measured with a diametral extensometer and converted to axial strain by an on-line strain computer so that strain rate and strain range were controlled axially. The diametral extensometer was not used on any weld metal specimens since a value for ν/E (Poisson's Ratio/Elastic Modulus) is required to program the strain computer and the weld metal exhibited relatively large degrees of anisotropy with respect to these material constants[2,3]. The tests were conducted in air using induction heating. Temperature control and monitoring were accomplished by resistance welding thermocouples just above and below the gage section. Temperature profile was optimized across the gage length by adjusting induction coil configurations until a maximum gradient of 2.5 C (5F) was obtained on an instrumented specimen. The gage length temperature was then calibrated to the control and monitor positions so

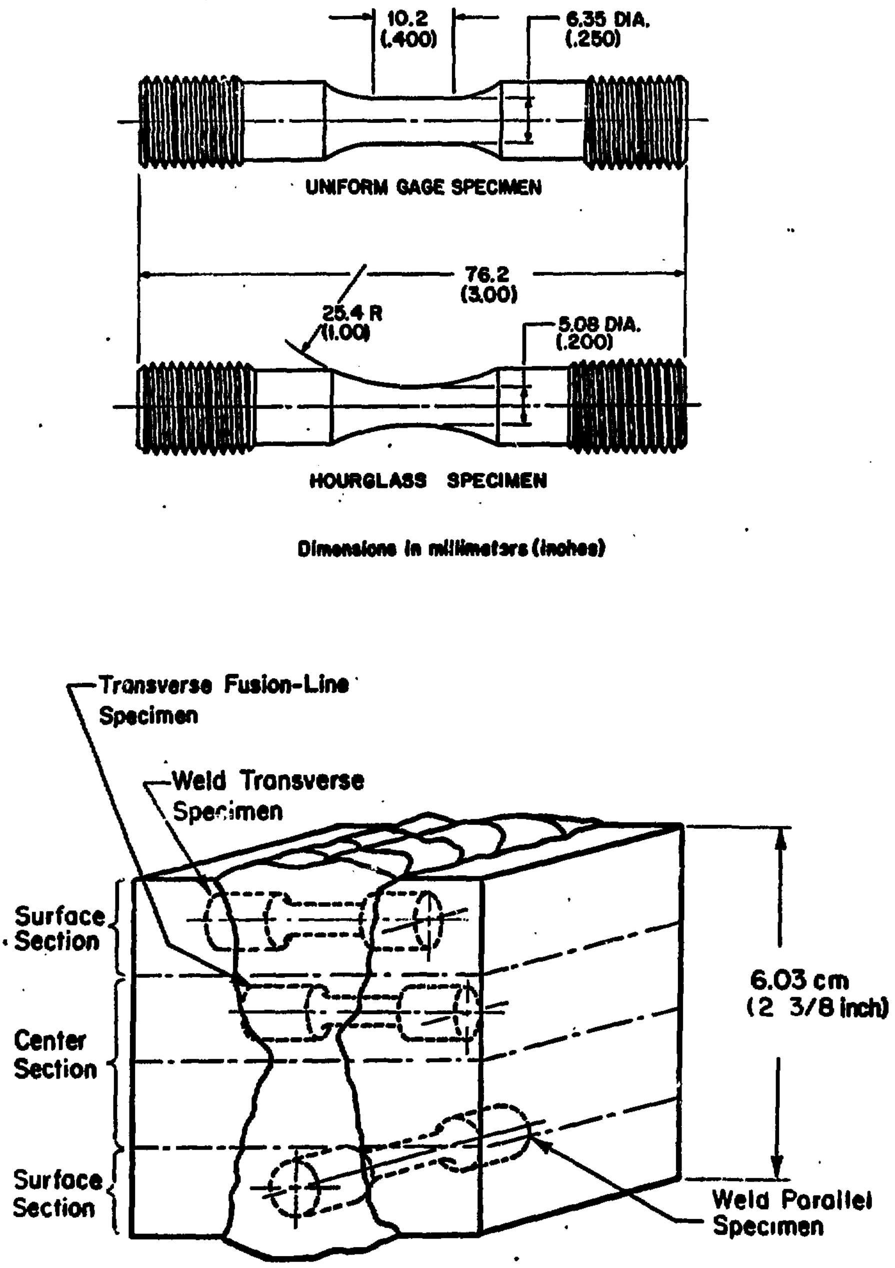

Figure 1 - Schematic diagram showing specimen details and relative positions of specimens with respect to weldment block.

that no thermocouples would be on the gage section during fatigue testing. Creep/fatigue interaction was investigated by incorporating tensile hold times at the peak tensile strain during each fatigue cycle. Since strain was held constant during the dwell period, stress relaxation occurred. Hold times varied from 0.01 to 0.5 h.

In conducting weld metal fatigue tests with a uniform gage specimen some difficulty was experienced in defining failure. The weld metal exhibited cyclic softening[2] and once a crack was initiated it grew relatively slowly and a considerable number of strain controlled cycles was required for complete separation. The decrease in stress due to the presence of a crack and the steady stress decrease due to softening were not always obviously distinguishable, especially at the lower strain ranges where cracks grew very slowly. The criteria used in this investigation to define failure was to make a plot of the stress range ($\Delta\sigma$) vs N/N_f' where N is the number of cycles and N_f' is the cycles where the specimen was either broken in two or obviously had a gross crack. A straight line was drawn parallel to the mid-portion of the $\Delta\sigma$-N/N_f' plot and displaced down by 5 per cent. Failure, N_f, was then defined where the two lines intersected. Failure for the hourglass specimens using a diametral extensometer was defined at specimen separation since relatively few cycles were required to fracture the specimen once a crack was initiated.

Irradiation was performed in Row 7 of the Experimental Breeder Reactor II (EBR-II) at 380-450 and 600 C. The lower temperature specimens were contained in weeper capsules which allowed reactor sodium to contact the specimens and the higher temperature was obtained by irradiating the specimens in argon-filled capsules. Irradiation temperature for the 600 C specimens was determined from theoretical calculations and melt wire monitors and is estimated to be within ±15 C of the target temperature of 593 C (1100 F). The lower temperature values were determined also from melt wires and a knowledge of the reactor sodium temperature and varied from 380 to 450 C depending on reactor position. Tests were conducted at 593 C (1100 F) and 482 C (900 F) on specimens corresponding to 600 C and 380-450 C radiation temperatures, respectively.

A limited number of tensile tests were performed on both irradiated and unirradiated specimens to obtain tensile properties at the same strain rate as the fatigue tests.

MATERIALS

Type 304 stainless steel plates (Ht 600414), 6.03 cm (2 3/8 inch) thick were machined with a double-U groove and welded using the shielded metal arc (SMA) process. The weld was a multiple pass weld with two passes per layer except at the weld root which had one pass. Type 308 weld wire with controlled residual elements from weld batch 4 and 6 was used as filler. Base metal, weld wire, joint configuration, and welding parameters are detailed elsewhere[2,4,5]. The plates were remnant pieces from the Fast Flux Test Facility (FFTF) vessel at Richland, Washington, and all welding parameters including the weld wire were maintained identical to that utilized in the fabrication of the FFTF vessel.

RESULTS

Fatigue tests

Data obtained from cyclic tests of the irradiated weld material are given in Table 1 and plotted in Fig. 2 for the 482 C (900 F) tests and Table 2 and Fig. 3 for the 593 C (1100 F) tests. Considerable cyclic softening occurred during the testing of the weld metal specimens and therefore the stress range is given at various points during the cycle life so that stress is described throughout the test. The following symbols are defined for Tables 1 and 2:

$\Delta\varepsilon_t$ = total strain range

$\Delta\varepsilon_p$ = plastic strain range

$\Delta\sigma$ = stress range

σ_t = peak tensile stress amplitude

N_f = cycles to failure

t_f = time to failure

Unirradiated and base metal data are also given for comparison except for the 593 C (1100 F) tests which have been reported previously[2,3]. Results show that at 593 C (1100 F) the fatigue life of weld metal specimens irradiated to 0.5 to 1.1×10^{22} n/cm^2, E>0.1 MeV, has been reduced by approximately one-half in the low cycle region (<5×10^3 cycles to fail), but in the high cycle region (>10^4 cycles to fail) irradiated material was equivalent or slightly superior to the unirradiated weld metal. At 482 C (900 F) with a neutron exposure of 1.0 to 1.4×10^{21} n/cm^2, E>0.1 MeV, the fatigue life was not reduced as much by the irradiation as at the higher temperature and

Table 1 - Strain Fatigue Behavior of Type 304/308 Stainless Steel Weldments Tested[a] at 482 C (900 F)

Specimen No.	Condition[b]	$\Delta\epsilon_t$, %	$\Delta\epsilon_p$, %	$\Delta\sigma$ at First Cycle		$\Delta\sigma_{max}$		Cycle of $\Delta\sigma$ Max.	$\Delta\sigma$ at $N_f/2$		σ_t at $N_f/2$		$\Delta\sigma_t$ at ~3/4 N_f		N_f	$t_{f,h}$
				MPa	ksi	MPa	ksi		MPa	ksi	MPa	ksi	MPa	ksi		
BT-100	Base 2a-T-S	2.02	1.53	356.5	51.7	833.6	120.9	137	799.8	116.0	384.7	55.8	789.5	114.5	685	1.85
BT-72	Base 2a-T-S	2.00	1.33	373.7	54.2	842.5	122.2	175	806.0	116.9	386.1	56.0	780.5	113.2	594	1.59
BT-23	Base 2a-T-C	0.99	0.59	393	57.0	605.4	87.8	370	555.0	80.5	281.3	40.8	533.0	77.3	3,809	5.20
BT-24	Base 2a-T-S	0.79	0.44	398.5	57.8	520.6	75.5	440	482.6	70.0	239.9	34.8	464.0	67.3	7,662	8.50
BT-25	Base 2a-T-S	0.50	0.21	322.7	46.8	----	-----	---	416.4	60.4	208.2	30.2	-----	-----	28,176	19.60
BT-28	Base 2a-T-S	0.37	0.03	289.6	42.0	582.6	84.5	61,500	544.7	79.0	251.0	36.4	570.9	82.8	692,520	381.30
BT-22	Base 2a-T-C	0.33	0.01	-----	-----	-----	-----	-----	359.2	52.1	164.8	23.9	----	-----	984,324[f]	467.10[f]
WF-42	Weld 2a-FL-C	1.98	1.46	696.4	101.0	633.6	120.9	80	830.1	120.4	399.2	57.9	821.2	119.1	262	0.70
WT-58	Weld 2a-T-S	2.02	1.50	692.9	90.2	732.2	106.2	42	723.3	104.9	367.5	53.3	717.1	104.0	364	0.98
WT-26	Weld 2a-T-C	1.98	1.35	639.2	92.7	654.3	94.9	6	608.1	88.2	295.1	42.8	601.2	87.2	588	1.31
C2C6 (1.09)	Weld 2i-T-C	1.93	1.40	862.5	125.1	900.5	130.6	4	801.9	116.3	388.9	56.4	792.2	114.9	347	0.94
WP-76	Weld 2a-P-C	1.92	1.36	757.1	109.8	757.0	109.8	1	694.3	100.7	327.5	47.5	682.6	99.0	531	1.42
WP-21 (1.38)	Weld 2i-P-C	1.95	1.34	903.9	131.1	922.5	133.8	3	760.5	110.3	348.2	50.5	743.3	107.8	513	1.39
WF-57	Weld 2a-FL-S	0.98	0.55	599.9	87.0	644.0	93.4	50	612.9	88.9	313.7	45.5	590.9	85.7	1,583	2.21
WT-60	Weld 2a-T-S	1.01	0.57	-----	-----	619.2	89.8	160	599.2	86.9	293.7	42.6	585.4	84.9	1,042	1.43
WT-42	Weld 2a-T-C	1.00	0.54	744.6	108.0	744.6	108.0	1	641.2	93.0	303.4	44.0	622.6	90.3	1,434	1.96
D2B6(1.07)	Weld 2i-T-S	0.99	0.53	775.7	112.5	782.6	113.5	10	686.7	99.6	337.2	48.9	667.4	96.8	875	1.19
WP-59	Weld 2a-P-S	0.98	0.50	497.8	72.2	538.5	78.1	93	487.5	70.7	232.4	33.7	470.9	68.3	4,094	5.60
WP-19 (1.42)	Weld 2i-P-S	0.99	0.47	688.1	99.8	688.1	99.8	1	580.5	84.2	286.1	41.5	566.8	82.2	4,821	6.58
WT-16 (0.94)	Weld 2i-T-S	0.80	0.36	775.0	112.41	775.0	112.4	1	664.7	96.4	312.3	45.3	650.2	94.3	2,022	2.21
WF-38	Weld 2a-FL-C	0.51	0.16	601.2	87.2	601.2	87.2	1	482.6	70.0	255.1	37.0	499.9	72.5	9,020	6.10
WT-22	Weld 2a-T-C	0.50	0.12	654.3	94.9	654.3	94.9	1	552.3	80.1	257.2	37.3	544.7	79.0	6,053	4.14
WP-79	Weld 2a-P-C	0.50	0.09	-----	-----	-----	-----	---	508.1	73.7	257.2	37.3	-----	-----	42,160	28.73
WT-59	Weld 2a-T-S	0.49	0.12	500.6	72.6	506.1	73.4	235	485.4	70.4	25.2	36.6	48.6	69.7	13,195	9.76
WT-29 (1.29)	Weld 2i-T-S	0.45	0.09	520.6	75.5	552.3	80.1	10	497.8	72.2	259.9	37.7	495.0	71.8	30,968	19.23
WT-56	Weld 2a-T-S	0.40	0.09	496.4	72.0	501.3	72.7	167	477.1	69.2	243.4	35.3	465.4	67.5	10,058	5.50
WT-46	Weld 2a-T-C	0.37	0.03	351.6	51.0	366.1	53.1	10	335.8	48.7	177.2	25.7	335.8	48.7	27,917	14.09
WP-77	Weld 2a-P-C	0.37	0.11	275.1	39.9	-----	-----	---	406.1	58.9	186.2	27.0	-----	-----	124,329	68.38
WP-70 (1.40)	Weld 2i-P-C	0.40	0.03	488.2	70.8	488.2	70.8	1	477.8	69.3	237.2	34.4	-----	-----	207,346[f]	112.9[f]
BT-26[c]	Base 2a-T-C	0.98	0.62	-----	-----	-----	-----	---	553.7	80.3	273.7 [268.9]	39.7[e] [39.0]	-----	-----	3,818	43.4
BT-27[d]	Base 2a-T-C	0.98	0.60	-----	-----	-----	-----	---	602.6	87.4	297.8 [288.9]	43.2[e] [41.9]	-----	-----	3,563	353.8
D2C7[d] (1.30)	Weld 2i-T-C	1.00	0.56	866.0	125.6	866.0	125.6	1	721.9	104.7	339.9 [315.8]	49.3[e] [45.8]	707.8	102.7	1,050	106.4

[a]Triangular waveform with strain rate of $4\times10^{-3}s^{-1}$

[b]2=Base metal heat 600414
a=As welded condition
i=Irradiated to fluence shown in ( ) in units of 10^{21} n/cm^2 (E>0.1 MeV at 360-450 C
T=Specimen taken transverse to weld seam
P=Specimen taken parallel to weld seam
FL=Transverse specimen across fusion line
S=Taken from section near surface of weldment
C=Taken from section near center of weldment

[c]Tensile hold time of 0.01 hr on each cycle

[d]Tensile hold time of 0.1 hr. on each cycle

[e]First number is tensile stress at beginning of hold period and second number in [ ] is tensile stress at end of hold

[f]Did not fail

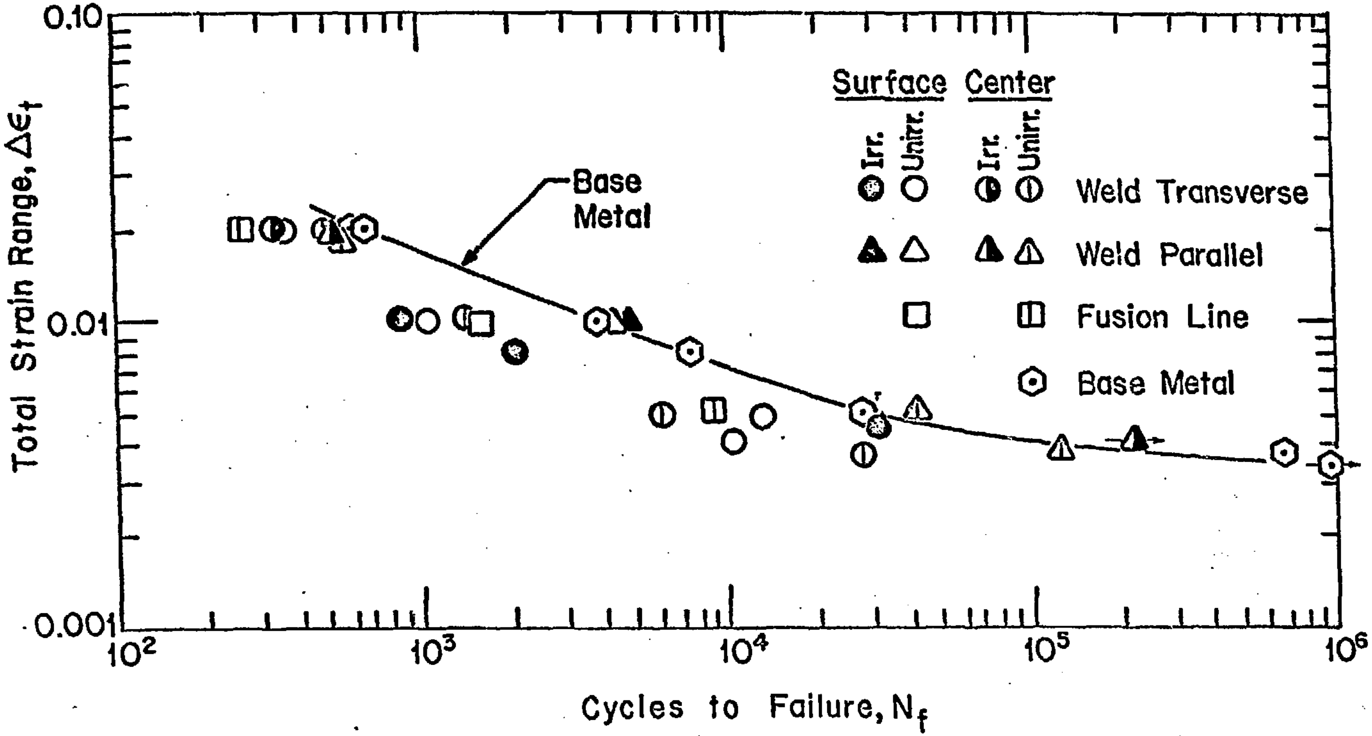

Figure 2 - Strain fatigue behavior of irradiated and unirradiated Type 304/308 stainless steel weldment material tested at 482 C (900 F). Fluence levels 1.0 to 1.4×10^{21} n/cm^2, E>0.1 MeV.

Table 2 – Strain Fatigue Behavior of Irradiated SMA Type 308 Stainless Steel Weld Metal Tested[a] at 593 C (1100 F)

Specimen No.	Condition[b]	$\Delta\varepsilon_t$ %	$\Delta\varepsilon_p$ %	Δσ at First Cycle		$\Delta\sigma_{max}$		Cycle of $\Delta\sigma_{max}$	Δσ at $N_f/2$		σ_t at $N_f/2$		Δσ ~3/4 N_f		N_f	t_f, h
				MPa	ksi	MPa	ksi		MPa	ksi	MPa	ksi	MPa	ksi		
WT-20 (6.64)	Weld 2I-T-S	2.00	1.65	735.0	106.6	786.0	114.0	4	721.9	104.7	352.3	51.1	710.2	103.0	196	0.53
WP-54 (10.21)	Weld 2I-P-S	2.03	1.55	575.7	83.5	653.6	94.8	6	621.9	90.2	301.3	43.7	616.4	89.4	372	1.0
WT-41 (8.38)	Weld 2I-T-S	1.00	0.63	620.5	90.0	672.0	97.9	10	619.8	89.9	303.4	44.0	606.7	88.0	641	0.87
WP-40 (9.60)	Weld 2I-P-C	1.00	0.59	584.7	84.8	605.4	87.8	6	503.3	73.0	245.5	35.6	495.0	71.8	1,040	1.42
WF-32 (8.08)	Weld 2I-FL-S	1.01	0.56	595.0	86.3	648.0	94.1	13	621.9	90.2	297.9	43.2	612.3	88.8	441	0.61
C2T3 (5.70)	Weld 2I-T-S	0.50	0.12	521.2	75.6	526.8	76.4	10	437.8	63.5	184.1	26.7	423.3	61.4	15,060	10.27
WP-35 (3.97)	Weld 2I-P-S	0.50	0.19	507.5	73.6	506.1	73.4	3	386.1	56.0	182.7	26.5	368.9	53.5	12,377	8.42
D2C1 (11.14)	Weld 2I T-C	0.38	0.06	495.0	71.8	495.0	71.8	1	439.9	63.8	213.7	31.0	432.2	62.7	16,082	8.14

[a] Triangular waveform with strain rate of $4 \times 10^{-3}\ s^{-1}$

[b] 2=Base metal heat 600414
I=Irradiated to fluence shown in ( ) in units of $10^{21}\ n/cm^2$ (E> 0.1 MeV) at 580-610 C
T=Specimen taken transverse to weld seam
P=Specimen taken parallel to weld seam
FL=Transverse specimens across fusion line
S=Taken from section near surface of weldment
C=Taken from section near center of weldment

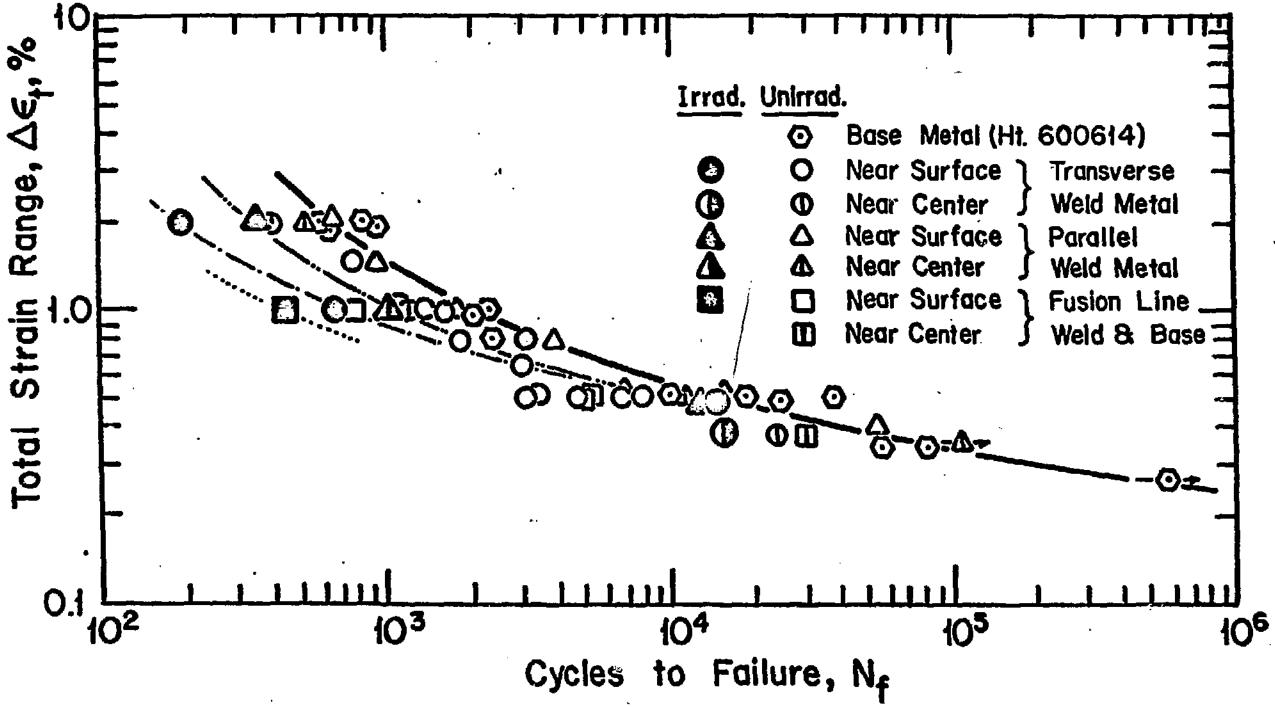

Figure 3 - Effects of irradiation on the strain fatigue behavior of Type 308 stainless steel weldment tested at 593 C (1100 F). Fluences are 0.5 to $1.1x10^{22}$ n/cm^2, E>0.1 MeV.

fluence, and the cross over point where the irradiated material became equivalent to the unirradiated material was at a higher total strain range. In the high cycle region the irradiated weld was equivalent to or slightly greater in fatigue resistance than the unirradiated base metal.

Orientation effects were seen at both temperatures and were maintained in both irradiated and unirradiated material. Specimens from a parallel orientation (specimen axis parallel to weld seam, see Fig. 1) showed a superiority in cyclic life over those taken transverse to the weld seam, especially at 482 C. The specimens with the fusion-line at mid-gage generally had the lowest cyclic life at both temperatures and irradiation conditions. However, as the total strain approached total elastic in the higher cyclic region the orientation effect became less and less significant. Even though the specimens from the center section of the weldment have been shown to be higher strength material[3,5], differences in fatigue life between surface and center specimens were not significant.

Creep/fatigue tests

To investigate creep/fatigue interaction of the weld metal, fatigue tests were conducted at one per cent total strain range at 593 C (1100 F) with a hold period at the maximum tensile strain of each cycle. Stress relaxation occurred during the constant strain dwell period as some of the elastic strain was converted to plastic strain. Creep damage occurred during the hold period and thus reduced the number of cycles to fail. The results of the fatigue tests with dwell periods are tabulated in Table 3 and plotted as time-to-fail vs cycles-to-fail plot (t_f-N_f) in

Fig. 4. Symbols in Table 3 have been defined previously except the new term, σ_t min, which is the tensile stress amplitude at the end of a hold period. This type of plot gives better resolution on the reduction of cyclic life as a function of hold time than a total strain range vs. cycles-to-fail ($\Delta\varepsilon_t$-N_f) plot and also allows extrapolations to longer hold periods. Zero hold time or straight fatigue cycling data are shown for a reference line. The weld metal, which had a lower cycle life at one per cent strain range and zero hold time, was less damaged by the hold times than the base metal and a cross over occurred at about a 0.1 h hold time. The parallel orientation again was seen to be superior to the transverse orientation. The depth in the weldment block had a much more pronounced effect in the hold time tests and, with few exceptions, the center section material had a longer life than the surface weld material. Considerable more scatter was introduced in the data due to irradiation but in general its effect was to offset the cyclic life to lower values with about the same rate of life reduction as hold periods increased. Compressive hold periods were not investigated in this work, but previous investigations for Type 304 and 316 stainless steel base metal in the irradiated and unirradiated condition show this type of loading to be much less damaging than the tensile hold[6,7].

Limited tests were conducted at 482 C (900 F) at one per cent total strain range and a 0.1 h and 0.01 h hold time. The stress relaxation was very small and there was no reduction in cyclic life. The data

Table 3 - Strain Fatigue Behavior of Type 304/308 Stainless Steel Weldments Tested[a] at 593 C (1100 F)

Specimen No.	Condition[b]	$\Delta\varepsilon_t$,%	$\Delta\varepsilon_p$,%	$\Delta\sigma$ at First Cycle		$\Delta\sigma_{max}$		Cycle of $\Delta\sigma$ max	$\Delta\sigma$ at $N_f/2$		σ_t at $N_f/2$		σ_t min at $N_f/2$		$\Delta\sigma$ at 3/4 N_f		N_f	t_f,h	Hold Time h
				MPa	ksi	MPa	ksi		MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi			
BT-97	Base 2a-T-S	0.99	0.62	-----	-----	557.8	80.9	30	563.3	81.7	268.9	39.0	-----	-----	550.2	79.8	2,119	2.88	0
BT-85	Base 2a T-S	0.99	0.60	389.6	56.5	597.8	86.7	195	561.9	81.5	270.3	39.2	-----	-----	538.5	78.1	2,292	3.18	0
A1C6	Base 2a-T-C	1.00	0.59	293.7	42.6	561.9	81.5	194	555.0	80.5	266.8	38.7	-----	-----	553.0	80.2	2,302	3.20	0
D2B8	Weld 2a-T-S	1.00	0.63	529.5	76.8	553.0	80.2	10	442.0	64.1	210.3	30.5	-----	-----	438.5	63.6	1,380	1.78	0
WT-26	Weld 2a-T-S	1.00	0.56	570.9	82.8	590.9	85.7	10	508.8	73.8	252.3	36.6	-----	-----	431.6	62.6	1,433	1.98	0
D2B4	Weld 2a-T-S	1.00	0.65	562.6	81.6	574.3	83.3	10	690.9	71.2	235.1	34.1	-----	-----	466.1	67.6	1,607	2.23	0
D2C6	Weld 2a-T-S	1.00	0.61	554.3	80.4	573.0	83.1	10	481.3	69.8	231.7	33.6	-----	-----	477.1	69.2	1,200	1.53	0
WT-41 (8.38)	Weld 2I-T-S	1.00	0.63	620.5	90.0	675.0	97.9	10	619.8	89.9	303.4	44.0	-----	-----	606.7	88.0	641	0.87	0
WP-62	Weld 2a-P-S	0.99	0.63	437.1	63.4	674.4	68.8	15	426.8	61.9	213.7	31.0	-----	-----	411.6	59.7	1,682	2.30	0
WP-24	Weld 2a-P-S	1.00	0.62	443.3	64.3	481.9	69.9	30	423.3	61.4	205.5	29.8	-----	-----	397.8	57.1	1,852	2.37	0
WP-40 (9.60)	Weld 2I-P-C	1.00	0.59	584.7	84.8	605.4	87.8	6	503.3	73.0	245.5	35.6	-----	-----	495.0	71.8	1,040	1.42	0
WF-29	Weld 2a-FL-S	1.05	0.59	536.4	77.8	589.5	85.5	---	575.0	83.4	286.1	41.5	-----	-----	554.3	80.4	770	1.07	0
WF-5	Weld 2a-FL-S	1.03	0.60	621.2	90.1	621.2	90.1	1	518.5	75.2	253.7	36.8	-----	-----	-----	-----	1,311	1.82	0
WF-32 (8.08)	Weld 2I-FL-S	1.01	0.56	595.0	86.3	648.8	94.1	13	621.9	90.2	297.9	43.2	-----	-----	612.3	88.8	441	0.61	0
BT-80	Base 2a-T-S	0.99	0.61	308.9	44.8	586.1	85.0	437	583.3	84.6	288.9	41.9	271.7	39.4	562.6	81.6	1,458	16.40	.01
BT-99	Base 2a-T-C	1.01	0.64	356.5	51.7	588.1	85.3	219	577.8	83.8	277.9	40.3	248.2	36.0	568.8	82.5	1,256	14.48	.01
WT-37	Weld 2a-T-S	1.00	0.66	528.8	76.7	558.5	81.0	5	481.3	69.8	227.5	33.0	202.7	29.4	464.7	67.4	1,135	11.18	.01
WT-30	Weld 2a-T-C	1.02	0.63	568.8	82.5	582.6	84.5	3	462.0	67.0	220.6	32.0	201.3	29.2	454.4	65.9	914	10.50	.01
WP-47	Weld 2a-P-S	1.00	0.68	409.6	59.4	423.3	61.4	3	359.9	52.2	177.2	25.7	241.3	35.0	350.3	50.8	2,010	23.13	.01
WP-52	Weld 2a-P-C	0.95	0.62	506.8	73.5	506.8	73.5	1	403.3	58.5	200.6	29.1	175.1	25.4	380.6	55.2	1,513	18.20	.01
WF-6 (6.83)	Weld 2I-FL-C	1.00	0.59	706.7	102.5	706.7	102.5	1	606.7	88.0	289.6	42.0	263.4	38.2	588.8	85.4	687	7.80	.01
BT-79	Base 2a-T-C	1.02	0.73	359.9	52.2	545.4	79.1	118	540.6	78.4	266.1	38.6	233.7	33.9	526.1	76.3	593	65.45	.1
A1C2	Base 2a-T-C	1.01	0.63	-----	-----	-----	-----	---	555.7	80.6	277.2	40.2	241.3	35.0	-----	-----	631	64.00	.1
WT-40	Weld 2a-T-S	1.00	0.64	539.2	78.2	539.2	78.2	1	452.3	65.6	204.8	29.7	-----	-----	450.9	65.4	992	102.01	.1
WT-11	Weld 2a-T-C	0.93	0.62	531.6	77.1	531.6	77.1	1	440.6	63.9	218.6	31.7	180.6	26.2	438.5	63.6	1,205	119.50	.1
WT-27	Weld 2a-T-C	1.01	0.67	537.8	78.0	578.5	83.9	2	515.7	74.8	237.9	34.5	197.9	28.7	526.8	76.4	1,124	118.20	.1
D2C2 (6.51)	Weld 2I-T-C	1.02	0.63	661.2	95.9	663.3	96.2	3	542.6	78.7	237.9	34.5	192.4	27.9	538.5	78.1	411	42.22	.1
D2B2 (10.06)	Weld 2I-T-S	1.02	0.66	598.5	86.8	625.4	90.7	5	539.9	78.3	257.2	37.3	206.8	30.0	530.9	77.0	427	43.90	.1
WP-64	Weld 2a-P-C	1.00	0.66	502.63	72.9	502.6	72.9	1	395.1	57.3	189.6	27.5	158.6	23.0	386.8	56.1	1,734	171.03	.1
WP-48	Weld 2a-P-S	1.00	0.68	430.2	62.4	539.2	63.7	4	382.0	55.4	191.0	27.7	162.7	23.6	389.6	56.5	1,334	131.34	.1
WP-15 (5.33)	Weld 2I-P-C	1.01	0.62	652.9	94.7	652.9	94.7	1	479.2	69.5	225.5	32.7	196.5	28.5	470.9	68.3	1,128	115.92	.1
A1B10	Base 2a-T-S	1.00	0.62	-----	-----	-----	-----	---	552.3	80.1	259.2	37.6	218.6	31.7	-----	-----	588	294.80	.5
WT-55	Weld 2a-T-S	0.95	0.62	551.6	80.0	551.6	80.0	1	533.0	77.3	220.6	32.0	182.0	26.4	462.0	67.0	920	461.30	.5
WT-21 (4.10)	Weld 2I-T-S	1.00	0.65	652.9	94.7	677.1	98.2	3	530.9	77.0	249.6	36.2	202.0	29.3	519.2	75.3	203	99.67	.5
WT-7 (9.74)	Weld 2I-T-C	1.00	0.65	614.3	89.1	624.0	90.5	3	508.8	73.8	242.7	35.2	199.3	28.9	495.0	71.8	490	263.00	.5
WP-66(5.67)	Weld 2I-P-S	1.01	0.64	601.2	87.2	601.2	87.2	1	475.7	69.0	223.4	32.4	185.5	26.9	468.8	68.0	466	230.55	.5
WP-46 (5.09)	Weld 2I-P-C	1.02	0.63	664.7	96.4	664.7	96.4	1	466.1	67.6	211.0	30.6	167.5	24.3	566.4	66.2	573	283.80	.5

[a] Triangular waveform with strain rate of $4\times10^{-3}s^{-1}$

[b] 2-Base metal heat [illegible]0414
a-As welded condition
T-Specimen taken transverse to weld seam
P=Specimen taken parallel to weld seam
FL=Transverse specimens across fusion line
S=Taken from section near surface of weldment
C=Taken from section near center of weldment
I=Irradiated to fluence shown in ( ) in units of 10^{21} n/cm^2 (E>.1 MeV) at 580-610 C

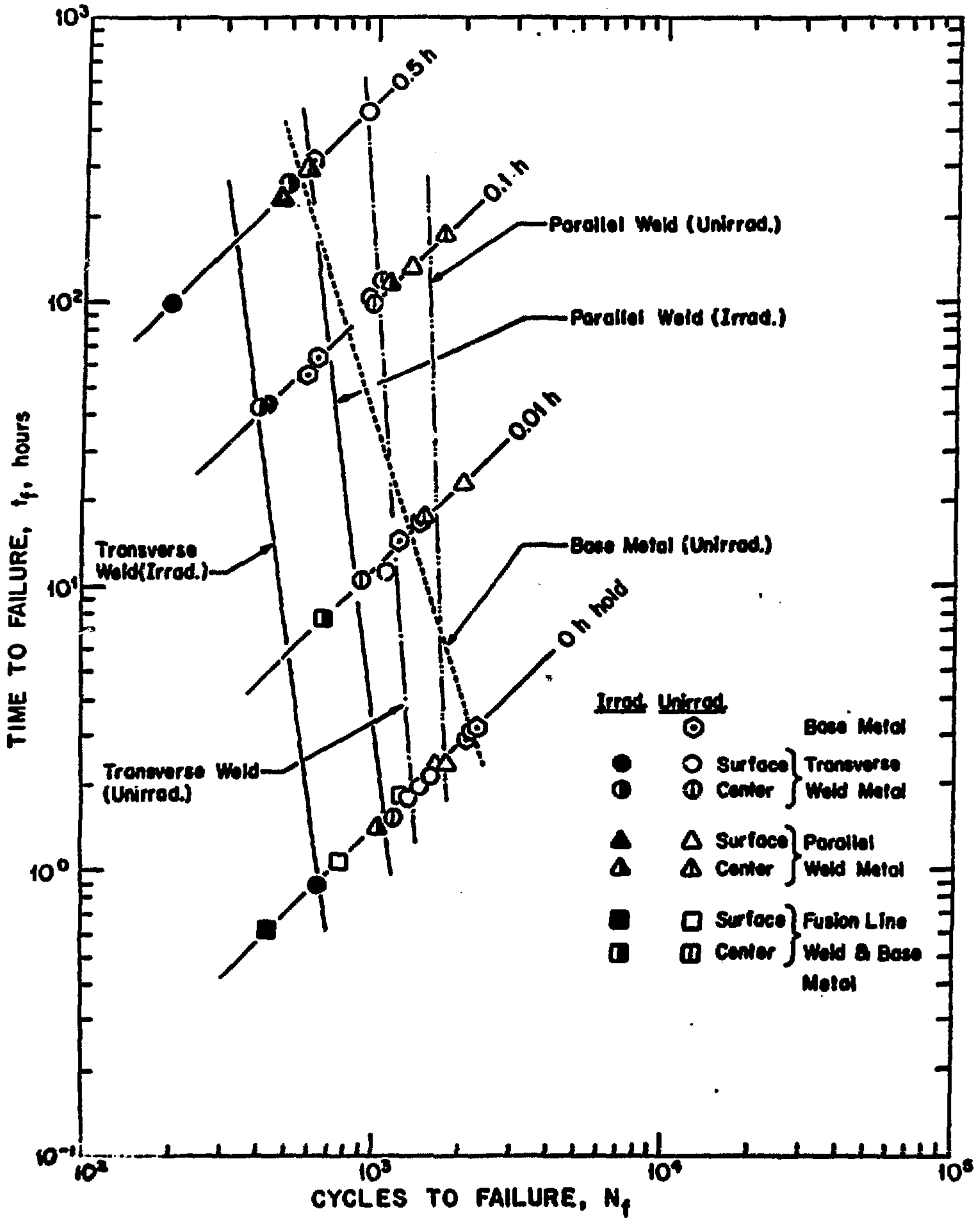

Figure 4 - Time to fail vs cycles to fail plot for irradiated and unirradiated Type 308 weld metal tested at 593 C (1100 F) at a total strain range of 1.0%. Fluence levels of 0.5 to 1.1×10^{22} n/cm², E>0.1 MeV.

for these tests are included in Table 1.

Tensile tests

Results of limited tensile tests of irradiated and unirradiated weld metal are reported in Table 4. The irradiated material increased in yield and ultimate strength and was reduced in ductility as is normally observed with metals subjected to neutron radiation. Tensile tests of irradiated material was conducted only on transverse specimens due to the limited number of irradiated parallel specimens available.

DISCUSSION

The objective of this investigation was to determine the effects of neutron irradiation on the fatigue and creep/fatigue properties of Type 308 stainless steel weld metal utilizing the joint design and material that was used in fabricating the FFTF vessel. The most desirable test would have been fatigue cycling of a full section weldment, but laboratory size specimens cut from the weldment have been successful in characterizing the cyclic properties of the material and have probably exhibited the extremes in performance that might be expected from a Type 304 stainless steel full size welded joint. The authors recommended that some caution be used in judging the transverse fusion line specimen as the worst case since there probably was a large strain gradient within the gage length due to the microstructural discontinuties at the weld-base metal interface. For this reason only a limited number of fusion line specimens were tested. Undoubtedly there was some strain gradients in the other weld metal specimens,especially the transverse orientation, but it is felt that due

Table 4 - Tensile Results of Type 308 Stainless Steel Weld Metal Tested at a Strain Rate of $4x10^{-3}s^{-1}$

Specimen No	Condition[a]	Yield Strength MPa	Yield Strength ksi	Ultimate Strength MPA	Ultimate Strength ksi	Total Elong in 10 mm, %	Reduction in Area, %	Test Temperature Deg C
WT-49	Weld 2a-T-S	243.4	35.3	356.5	51.7	44	45	593
WP-61	Weld 2a-P-S	211.0	30.6	333.7	48.4	50	48	593
D2B9 (4.66)	Weld 2I-F-S	282.7	41.0	380.6	55.2	32	33	593
WT-57	Weld 2a-T-S	284.1	41.2	439.9	63.8	52	39	482
WT-34	Weld 2a-T-C	319.2	46.3	438.5	63.6	40	42	482
WP-80	Weld 2a-P-C	325.4	47.2	427.5	62.0	42	50	482
D285 (1.16)	Weld 2i-T-S	408.9	59.3	492.3	71.4	28	38	482
D2C4 (0.96)	Weld 2i-T-C	467.5	59.1	501.9	72.8	33	32	482

[a] 2=Base metal heat 600414
a=As welded condition
T=Specimen taken transverse to weld seam
P=Specimen taken parallel to weld seam
FL=Transverse specimens across fusion line
S=Taken from section near surface of weldment
C=Taken from section near center of weldment
I=Irradiated to fluence shown in ( ) in units of $10^{21}n/cm^2$ (E>.1 MeV) at 580-610 C
i=Irradiated to fluence shown in ( ) in units of $10^{21}n/cm^2$ (E>.1 MeV) at 380-450 C

to the relatively short gage length, the gradients were minimized and the results will be meaningful for design guidance and show good comparisons with base metal and the effects of irradiation.

The effects of orientation on the cyclic life are believed to be largely due to the substructure of the solidified weld metal. Transverse specimens contain the major part of two weld passes in the gage section and the loading direction is perpendicular to the long columnar grains resulting from solidification of the molten weld metal. The parallel oriented specimens would tend to be much more homogeneous with respect to the substructure perpendicular to the loading axis and the effect of interpass boundaries would be minimized with this orientation. Since the addition of a hold time to the fatigue cycling emphasizes even more the effect of grain boundaries[8], the gap between parallel and transverse behavior became greater during the creep/fatigue tests.

A method has been proposed to predict the effects of irradiation on fatigue behavior when unirradiated fatigue data and irradiated and unirradiated tensile data are available[9]. This method, called the Fraction Modification Method, is a fraction adjustment to both terms of the equation:

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p = \phi_u A N_f^{\,a} + \phi_t B N_f^{\,b} \qquad (1)$$

where $\Delta\varepsilon_e$ is the elastic strain range, A, a, B, and b are constants determined from unirradiated fatigue data, and $\Delta\varepsilon_t$, $\Delta\varepsilon_p$ and N_f are the same as defined previously. The fraction modifications are ϕ_u and ϕ_t which are defined by :

$$\phi_u = \frac{(\sigma_{uts})\text{irrad}}{(\sigma_{uts})\text{ unirrad}} \qquad\qquad \phi_t = \left(\frac{D\text{ irrad}}{D\text{ unirrad}}\right)^{0.6}$$

where σ_{uts} is the ultimate tensile strength and D is fracture ductility

$[=\ln(\frac{1}{1-RA})]$. RA is the reduction in area and the 0.6 exponent comes from the Universal Slopes Eq which is the basis for the Fraction Modification Method. Previous investigations [6,9] have shown this method to be of value in predicting irradiation effects of fatigue data. The method was employed in this investigation and results are compared to the irradiated transverse weld metal in Fig. 5. Sufficient irradiated parallel specimens were not available for tensile tests to allow comparisons with both orientations. Fig. 5 shows the prediction to be slightly non-conservative at the higher strain ranges where the ductility component of Eq 1 is dominant. This is probably due to the fact that the irradiated tensile data was obtained from specimens that were at the bottom of the fluence range at both temperatures. Tensile data from higher fluence specimens would have resulted in lower reduction-in-area values and thereby reduced the value of ϕ_t which would bring the prediction curve down in the low cycle region.

The creep/fatigue data were somewhat surprising in that the effects of tensile hold periods were much less damaging in the weld metal than with the base metal. In another investigation[2] a particular heat of Type 304 stainless steel exhibited superior creep/fatigue properties, much like the weld metal reported here, but that heat of stainless was

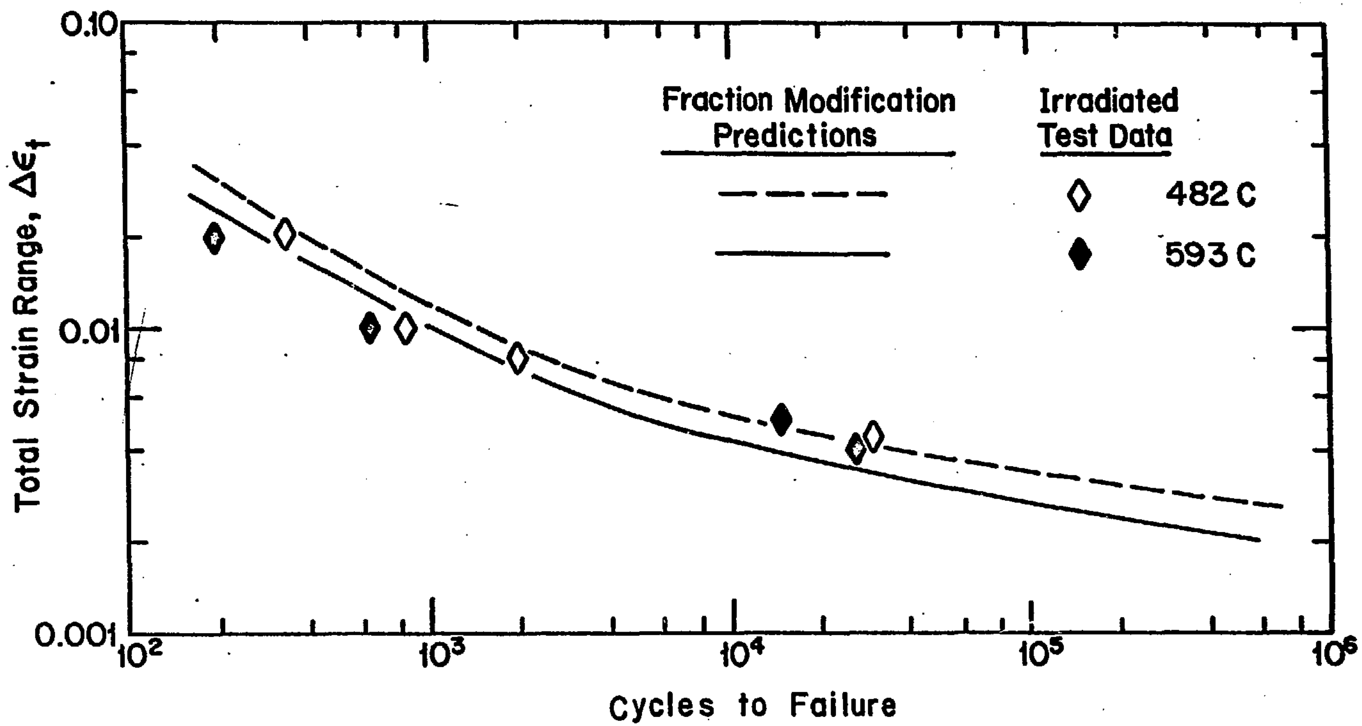

Figure 5 - Comparisons of irradiated transverse Type 308 stainless steel weld metal fatigue data to the fraction modification predictions.

also reported to have superior creep properties. Creep studies of the weld metal used in this investigation have shown that the weld material was equivalent but not necessarily superior to the base metal[10]. The reason for the higher creep/fatigue resistance of the weld metal was probably due to the extensive cyclic softening experienced by the weld material. Even though the amount of stress relaxation during hold periods was approximately the same for base and weld metal, the mean tensile stress amplitude during a hold time was lower for the weld metal the major part of the cycle life. This behavior is illustrated in Fig. 6 for unirradiated material. Irradiation resulted in significant decreases in the cycles to fail and introduced considerable scatter in the data. Irradiation probably interacted differently with the various species of the heterogeneous substructure resulting in early crack initiation in some cases and not in others. Helium bubbles from n,α reactions collecting at the grain boundaries or austenite-ferrite interfaces also undoubtedly played a significant role in the cyclic life when dwell periods could assist in their agglomeration.

CONCLUSIONS

From the results of the low cycle fatigue tests with and without hold times on irradiated and unirradiated Type 308 weld metal the following conclusions were drawn:

1. Irradiation to fluences of 0.5 to 1.1×10^{22} n/cm^2, E>0.1 MeV at 580–610 C resulted in reductions in fatigue life at 593 C when N_f was below about 5000. But in the higher cycle region, irradiated

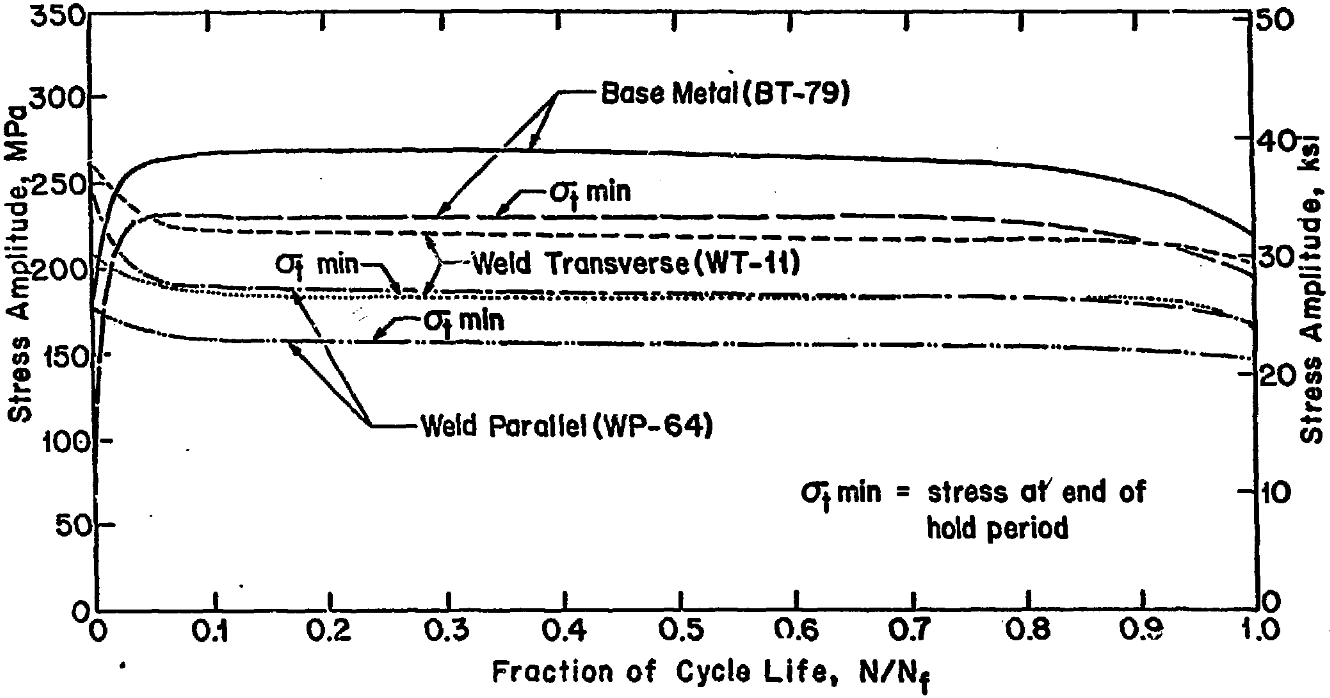

Figure 6 - Comparison of tensile stress amplitude at beginning and end (σ_t min) of hold period of base and weld metal as a function of cycle life.

and unirradiated fatigue behavior was equivalent. At the lower test temperature (482 C) and with fluences of 1 to 1.4×10^{21} n/cm^2 E>0.1 MeV at 380-450 C fatigue behavior of the irradiated weld metal was only slightly inferior to the unirradiated material and then only in the low cycle region.

2. Changes in irradiated fatigue behavior could be primarily related to changes in strength and ductility which allowed the Fraction Modification Method to be utilized in predicting irradiated properties.

3. Tensile hold times introduced into the fatigue cycling at 593 C produced less creep damage in the weld metal than the parent material since the stress relaxation of the weld occurred at a lower mean stress. Irradiation caused further reductions in the creep/fatigue interaction tests and the increased data scatter was attributed to inhomogeneous neutron damage of the various species of the weld substructure. Hold times had no significant effect on either base metal or irradiated weld metal at 482 C.

Acknowledgement

The work described in this paper was performed under the auspices of the United States Atomic Energy Commission under Contract AT(10-1)-1375. We gratefully acknowledge the support of the Fuels and Materials Branch, USAEC in this endeavor.

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