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COMPARISON OF THE FATIGUE AND CREEP-FATIGUE
PROPERTIES OF UNIRRADIATED AND IRRADIATED
TYPE 304 AND 316 STAINLESS STEEL AT 593°C (1100°F)

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BY Jack H. Kahn /wer
DATE 10/24/72

MASTER

DATE PUBLISHED - AUGUST 1972

PREPARED FOR THE

U. S. ATOMIC ENERGY COMMISSION

IDAHO OPERATIONS OFFICE UNDER CONTRACT AT(10-1)-1375

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

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**COMPARISON OF THE FATIGUE AND CREEP-FATIGUE
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ACKNOWLEDGMENTS

The authors would like to express their appreciation to M. D. Harper and G. A. Rigby who helped with the experimental tests. Also, they gratefully acknowledge the support provided by the U. S. Atomic Energy Commission, Fuels and Materials Branch, Division of Reactor Development and Technology.

ABSTRACT

Results from fully reversed strain-controlled fatigue tests conducted at 593°C (1100°F) with and without tensile hold times on irradiated and unirradiated AISI 304 and 316 stainless steel are reported. Corresponding data from constant strain rate tensile tests conducted at the same temperature and strain rate are also given.

Comparing data obtained from tests conducted on unirradiated Type 316 stainless steel in either the solution annealed or solution annealed and aged condition showed that aging was beneficial in improving both the fatigue and creep-fatigue properties at this temperature. An indication was found that unirradiated Type 304 stainless steel would be more suitable for applications involving creep-fatigue interaction than unirradiated Type 316 stainless steel. Irradiation to fluences of 0.17 to 6.1×10^{21} n/cm² E > 0.1 MeV (450°C) resulted in a pronounced effect on the creep-fatigue resistance of these materials when tested at a strain range of 1%. Data comparisons between irradiated and unirradiated, both aged and solution annealed, material were made by means of a time to fail versus number of cycles to failure diagram. Testing was also conducted on some specimens that had been cold-worked 11% prior to specimen fabrication. Little or no effect of cold-work was found for unirradiated Type 316 stainless steel. Creep and fatigue damage values were calculated using actual failure data and design criteria suggested by ASME Code Case 1331-5, and comparisons were made. Damage sums obtained were not found to be a unique value but dependent upon strain range, length of tensile hold time, and material condition.

The inelastic strain developed during the various tests was partitioned into values resulting from creep and plastic flow for both irradiated and unirradiated material. Equations relating partitioned inelastic strain to cycle life for design estimates involving fully reversed hysteresis loops with creep flow in tension are given.

Comparisons between estimates of irradiated fatigue behavior and actual irradiated fatigue lifetimes were made using limited data available. Estimates made using irradiated tensile data were usually found to be conservative in predicting pure fatigue behavior.

Bilinear constants used for defining the cyclically hardened uniaxial stress-strain curve for the kinematic hardening model were also determined.

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COMPARISON OF THE FATIGUE AND CREEP-FATIGUE PROPERTIES OF UNIRRADIATED AND IRRADIATED TYPE 304 AND 316 STAINLESS STEEL AT 593°C (1100°F)

I. INTRODUCTION

Design of liquid metal cooled fast breeder (LMFBR) systems requires that the design engineer take into account structural material behavior at elevated temperatures. Metallurgical changes as well as material behavior normally associated with elevated temperatures such as stress relaxation, creep, strain rate sensitivity, cyclic hardening or softening, creep-fatigue interaction, and a decrease in resistance to fatigue must all be considered. The problem of fatigue and creep-fatigue interaction of stainless steels subject to combinations of static and cyclic loading at elevated temperatures has received considerable attention, [1-5], and while complete agreement as to how to deal with the problem for design purposes has not been attained, trends are emerging. ASME Code Case 1331-5 suggests an approximate method of accounting for both creep and fatigue damage in unirradiated materials. Additional Code Cases will be required as more elevated temperature data become available and, in the interim, conservative estimates of both irradiated and unirradiated material behavior at elevated temperatures will have to be made. The objectives of this report are to (a) present fatigue, creep-fatigue, tensile, and cyclic hardening data recently obtained from tests conducted on irradiated and unirradiated, annealed, aged, or cold worked 304 and 316 stainless steels, (b) examine methods of estimating fatigue and creep-fatigue properties, and (c) compare irradiated and unirradiated material behavior according to methods of estimation prescribed by Code Case 1331-5.

II. TEST DESCRIPTION

1. MATERIALS

Materials utilized in these tests were obtained from the AEC standard heat stockpile^[6] and consisted of 5/8-inch diameter AISI Type 304, Heat No. 55697, and Type 316, Heat No. 65808, stainless steel rod. The materials in the as-received condition were essentially in the solution annealed and straightened condition with an ASTM grain size of 3-5. Some of the rods were given an 11% reduction in area at room temperature prior to specimen fabrication, hereafter referred to as cold-worked material. Hourglass-shaped specimens with a 0.2-inch minimum diameter were fabricated from these rods, the details of which have been reported elsewhere^[4]. Some specimens were irradiated in EBR-II in sodium bonded capsules, in a row seven position, to fluences of 1.7 to 60.9×10^{20} n/cm² $E > 0.1$ MeV (450°C). Specimens were tested in the solution annealed, aged, cold-worked, and irradiated condition as identified in Tables I through IV.

2. EXPERIMENTAL PROCEDURE

Specimens were tested in closed-loop electrohydraulic test machines. Two test frames were situated in the large atmosphere box shown in Figure 1. The box in turn was surrounded with lead brick. The atmosphere box permitted testing in an inert atmosphere; however, all of the data reported herein were from specimens tested in air. Irradiated specimens were remotely fitted with extension rods as shown in Figure 2. The specimen extension-rod train was positioned in the atmosphere enclosure as shown in Figure 3 and loaded into self-aligning hydraulic grips for testing. The extension rods permitted rapid loading of the specimen into the self-aligning grips. Alignment checks of the irradiated specimen extension rod chain were not possible but were performed on unirradiated specimens. The criterion used for alignment was that elastic cycling of the specimen (± 600 lb or ± 19.1 ksi) should not produce a lateral displacement in excess of ± 0.002 inch as measured by a dial indicator gauge. Specimens were heated to the desired test temperature by induction heating and tested as shown in Figure 4. A rack and pinion motor-driven device permitted X-Y-Z remote positioning of the induction coil. Temperature was measured by thermocouples attached approximately 3/16 inch above and below the specimen center line. Specimen temperature was maintained at 1100°F (593°C) $\pm 5^\circ\text{F}$ throughout each test.

All fatigue and creep-fatigue test data reported were obtained from axial strain controlled fully reversed cyclic tests with and without tensile and compressive hold times at a strain rate of 4×10^{-3} sec⁻¹. Continuous diametral strain measurements were made throughout each test using a diametral extensometer (Figures 4 and 5), and axial control was obtained by means of an axial strain computer^[7]. Monotonic and cyclic stress-strain curves were generated using a constant strain rate of failure of 4×10^{-3} sec⁻¹^[8]. Fatigue tests were always started with the first quarter cycle in tension.

TABLE I

FATIGUE AND CYCLIC DATA FOR TYPE 316 STAINLESS STEEL TESTED AT 593°C

Specimen No.	Condition	$\Delta\epsilon_f$ % [i]	$\Delta\epsilon_p$ %	$\Delta\epsilon_e$ % [i]	$\Delta\epsilon_{cp}$ %	$\Delta\sigma$ ksi [j]	σ_t max ksi	σ_t min ksi	N^S/N_f	N_f	t_f hrs	Creep Damage Per Cycle	Creep Damage N_5	Fatigue Damage $\Sigma N/N_f$	Total Damage	Tensile Hold Time, hr [e]	N_{cp}	N_{pp}	Mode of Crack Propagation [k]
D-143	Annealed [a]	2.0	1.45	0.55	0	128,400	61.5	61.5	0.92	450	1.25	3.8×10^{-5}	0.02	1.0	1.02	0	0	450	T
D-139	Annealed [a]	2.0	1.43	0.55	0	121,600	59.8	59.8	0.89	406	1.13	---	---	1.0	1.0	0	0	406	T
D-74	Annealed [a]	2.0	1.48	0.52	0	130,000	62.7	62.7	0.89	406	1.13	---	---	1.0	1.0	0	0	406	T
D-148	Annealed [a]	1.0	0.56	0.44	0	99,449	48.7	48.7	0.91	2,040	2.83	---	---	1.0	1.0	0	0	2,040	T
D-146	Annealed [a]	1.02	0.59	0.43	0	100,410	51.5	51.5	0.96	2,241	3.02	---	---	1.0	1.0	0	0	2,241	T
D-150	Annealed [a]	0.50	0.19	0.31	0	63,877	32.3	32.3	0.91	29,822	20.7	2.02×10^{-8}	5.7×10^{-4}	1.0	1.0	0	0	29,822	T
D-147	Annealed [a]	0.50	0.22	0.28	0	67,040	32.7	32.7	0.88	24,850	17.3	---	---	1.0	1.0	0	0	24,850	T
D-131	Annealed [a]	2.0	1.43	0.57	0.012	133,655	62.4	59.8	0.93	218	2.8	2.4×10^{-3}	0.49	0.51	1.01	0.01	432	440	M
D-186	Annealed [a]	1.98	1.57	0.56	0.016	120,101	60.1	56.5	0.95	367	4.7	1.5×10^{-3}	0.52	0.86	1.39	0.01	---	367	M
D-197	Annealed [a]	2.0	1.59	0.41	0.051	129,079	64.2	52.7	0.95	71	7.1	8.49×10^{-3}	0.57	0.17	0.74	0.1	90	373	M
D-200	Annealed [a]	2.0	1.58	0.42	0.043	123,585	60.9	51.2	0.90	115	11.82	7.32×10^{-3}	0.76	0.27	1.03	0.1	166	372	M
D-188	Annealed [a]	1.99	1.59	0.40	0.051	120,656	59.9	48.3	0.98	57	29.6	9.72×10^{-2}	0.48	0.14	0.80	0.5	67	373	I
D-129	Annealed [a]	2.0	1.57	0.43	0.051	104,716	56.3	44.7	0.95	64	32.18	1.26×10^{-2}	0.77	0.15	0.92	0.5	77	383	I
D-198	Annealed [a]	2.0	1.66	0.34	0.081	119,581	58.6	40.3	0.88	43	43.1	1.38×10^{-2}	0.52	0.10	0.62	1.0	49	354	I
D-144	Annealed [a]	2.0	1.61	0.39	0.081	103,829	52.5	34.3	0.88	24.9	127.6	1.69×10^{-2}	0.42	0.06	0.48	5.16	27	378	I
D-194	Annealed [a]	2.0	1.66	0.34	0.095	106,992	53.3	31.8	---	15.4	154.1	3.14×10^{-2}	0.48	0.04	0.52	10.0	16	360	I
D-142	Annealed [a]	1.0	0.57	0.43	0.015	103,200	49.7	46.2	0.80	1,179	13.32	1.95×10^{-4}	0.18	0.57	0.75	0.01	1,923	2,987	M
D-164	Annealed [a]	1.0	0.59	0.41	0.012	95,000	43.2	40.6	0.93	393	39.9	6.79×10^{-4}	0.25	0.19	0.40	0.1	458	2,749	M
D-184	Annealed [a]	1.0	0.58	0.42	0.012	95,846	48.1	45.5	0.86	433	44.4	2.06×10^{-3}	0.78	0.21	0.99	0.1	518	2,849	M
B-145	Annealed [a]	0.98	0.62	0.36	0.035	93,763	48.9	41.0	0.80	221	110.8	3.95×10^{-3}	0.70	0.10	0.80	0.5	241	2,683	I
D-173	Annealed [a]	1.0	0.67	0.33	0.057	94,910	44.0	41.0	0.61	84	420.6	5.23×10^{-3}	0.27	0.04	0.31	5.0	87	2,438	I
D-141	Annealed [a]	0.51	0.17	0.33	0.004	74,739	35.5	34.5	0.76	8,400	39.8	1.2×10^{-5}	0.08	0.31	0.39	0.01	11,045	35,075	M
D-177	Annealed [a]	0.5	0.16	0.34	0.004	73,504	34.3	33.5	0.78	1,985	199.9	9.74×10^{-5}	0.51	0.07	0.22	0.1	2,089	39,816	M
D-300	Annealed [a]	0.5	0.19	0.31	0.019	70,010	35.1	31.0	---	1,050	525.7	3.38×10^{-4}	0.36	0.04	0.40	0.5	1,084	33,014	I
D-162	Annealed [a]	0.5	0.27	0.23	0.023	69,020	33.2	27.9	0.80	812	813.1	2.48×10^{-4}	0.20	0.03	0.23	1.0	857	15,587	I
D-189	Annealed [a]	1.0	0.54	0.46	0.003	95,206	46.9	46.2 [C]	0.93	2,134	24.58	---	---	---	---	0.01 [C]	---	---	T
D-190	Annealed [a]	1.0	0.56	0.44	0.018	98,700	49.9	46.1 [C]	0.81	1,938	193.5	---	---	---	---	0.1 [C]	---	---	T
D-43	Control [b]	2.0	1.53	0.47	0	106,500	51.5	51.5	0.90	671	1.9	---	---	1.0	1.0	0	0	671	T
D-79	Control [c]	2.0	1.48	0.52	0	123,000	60.3	60.3	0.90	581	1.6	---	---	1.0	1.0	0	0	581	T
D-77	Control [c]	2.0	1.51	0.49	0	114,100	55.8	55.8	0.97	608	1.7	---	---	1.0	1.0	0	0	608	T
D-36	Control [b]	0.98	0.53	0.46	0	92,102	45.3	45.3	0.86	2,962	4.1	---	---	1.0	1.0	0	0	2,962	T
D-45	Control [b]	1.01	0.64	0.36	0	74,650	37.1	37.1 [B]	0.84	4,000	5.6	---	---	1.0	1.0	0	0	4,000	T
D-81	Control [c]	1.0	0.58	0.42	0	85,984	42.7	42.7	0.95	3,266	4.5	---	---	1.0	1.0	0	0	3,266	T
D-78	Control [c]	0.51	0.21	0.30	0	62,262	31.6	31.6	---	56,671	39.4	---	---	1.0	1.0	0	0	56,671	T
D-88	Control [c]	0.51	0.20	0.31	0	68,100	33.4	33.4	---	42,947	29.30	---	---	1.0	1.0	0	0	42,947	I
D-83	Control [c]	1.99	1.57	0.42	0.016	119,977	59.0	55.3	0.95	658	8.4	9.59×10^{-4}	0.60	1.0	1.7	0.01	0	658	M
D-85	Control [c]	2.0	1.49	0.51	0.030	115,146	57.7	50.9	0.97	203	20.9	5.94×10^{-3}	1.17	0.34	1.51	0.1	306	601	M
D-86	Control [c]	2.0	1.69	0.31	0.072	116,322	59.3	43.1	---	85	42.7	9.02×10^{-3}	0.77	0.14	0.91	0.5	103	479	I
D-82	Control [c]	2.0	1.62	0.38	0.058	100,236	51.0	37.9	0.88	146 [E]	292.4	1.12×10^{-2}	1.43	0.25	1.68	2.0	203 [E]	518	I
D-39	Control [b]	1.0	0.60	0.40	0.020	105,600	52.2	47.7	0.72	1,235	13.74	2.68×10^{-4}	0.241	0.42	0.66	0.01	1,678	4,678	M
D-38	Control [b]	0.99	0.56	0.43	0.020	94,553	47.1	42.5	0.79	560	56.78	9.71×10^{-4}	0.43	0.19	0.62	0.1	624	5,483	M
D-40	Control [b]	0.995	0.59	0.40	0.040	97,300	47.5	38.5	0.75	139	136.5	5.46×10^{-3}	0.57	0.09	0.66	1.0	143	5,264	I
D-87	Control [b]	0.49	0.22	0.27	0.00044	62,200	30.5	30.4	---	21,600 [E]	256.7	3.62×10^{-6}	0.08	0.43	0.51	0.01	46,267 [E]	40,515	No Fail
D-30	60.91 [d]	1.0	0.56	0.44	0	110,779	53.1	53.1	0.91	1,550	2.14	---	---	1.0	1.0	0	0	1,550	T
D-24	3.0 [d]	1.0	0.53	0.47	0.016	94,900	45.7	42.1	0.89	644	7.28	6.69×10^{-4}	0.38	0.42	0.91	0.01	922	2,136	I
D-22	16.1 [d]	1.0	0.67	0.33	0.027	82,400	40.3	34.1	0.89	113	11.18	1.91×10^{-3}	0.19	0.07	0.26	0.1	123	1,352	I
D-25	1.7 [d]	1.0	0.63	0.38	0.031	81,400	37.3	30.2	0.88	73	73.73	5.71×10^{-3}	0.37	0.05	0.42	1.0	77	1,562	I
D-29	28.6 [d]	1.0	0.66	0.33	0.041	81,102	38.6	29.3	0.72	57	56.5	5.68×10^{-3}	0.23	0.04	0.27	1.0	59	1,461	I
D-23	5.7 [d]	0.995	0.66	0.34	0.063	87,200	41.1	26.8	0.76	34	163.45	1.94×10^{-2}	0.50	0.02	0.52	5.0	35	1,573	I

Code: [a] Solution annealed 1/2 hour at 1075°C followed by helium quench.

[g] Indicates specimen did not fail.

[b] Aged 8760 hours at 400°C.

[h] Aged 8760 hours at 750°C.

[c] Aged 3096 hours at 600°C.

[i] Elastic strain range.

[d] Fluence $\times 10^{20}$ n/cm² E > 0.1 MeV (450°C).

[j] Stress range i.e. tensile plus compression amplitude.

[e] Tensile unless noted by (C) for compression hold times.

[k] T=transgranular, M=mixed, I=intergranular.

[f] Aged 3096 hours at 410°C.

[l] Strain rate, $\dot{\epsilon}$, = 4×10^{-3} sec⁻¹ = $2\Delta\epsilon_f$, where f = frequency.

TABLE II

FATIGUE AND CYCLIC DATA FOR TYPE 304 STAINLESS STEEL TESTED AT 593°C

Specimen No.	Condition	$\Delta\epsilon_t$ [d] %	$\Delta\epsilon_p$ %	$\Delta\epsilon_c$ %	$\Delta\epsilon_{cp}$ %	$\Delta\sigma$ ksi	σ_t , max ksi	σ_t , min ksi	N_5/N_f	N_f	t_f hrs	Creep Damage Per Cycle	Creep Damage $N_5 \int \frac{dt}{t_r}$	Fatigue Damage $\Sigma N/N_f$	Total Damage	Tensile Hold Time, hr	N_{cp}	N_{pp}	Mode of Crack Propagation [e]
A-31	Control [a]	1.0	0.63	0.37	0	77,697	38.9	38.9	0.94	2,737	3.80	---	---	1.0	1.0	0	0	2,737	T
A-67	Control [c]	0.995	0.64	0.34	0	78,706	38.8	38.8	0.92	2,904	4.03	---	---	1.0	1.0	0	0	2,904	T
A-32	Control [a]	1.0	0.64	0.35	0.012	78,352	39.0	36.4	0.89	1,190	13.55	6.31×10^{-4}	0.67	0.42	1.09	0.01	1,382	3,237	M
A-39	Control [a]	1.0	0.71	0.29	0.025	78,110	39.6	34.2	0.83	806	83.51	3.48×10^{-3}	2.33	0.29	2.62	0.1	1,156	2,656	M
A-33	Control [a]	1.0	0.71	0.29	0.032	69,100	33.4	26.6	0.84	593	585.41	2.26×10^{-3}	1.13	0.21	1.34	1.0	758	2,719	I
A-70	Control [c]	1.0	0.75	0.26	0.040	72,300	37.0	28.4	0.85	418	411.0	5.50×10^{-3}	1.96	0.15	2.11	1.0	504	2,449	I
Irradiated Data																			
A-21	38.1 [b]	1.0	0.63	0.33	0	81,318	40.0	40.0	0.82	1,996	2.77	---	---	1.0	1.0	0	0	1,996	T
A-22	16.5 [b]	1.0	0.71	0.30	0.023	66,097	32.5	27.6	0.82	256	25.95	8.98×10^{-4}	0.19	0.13	0.32	0.1	305	1,596	I
A-29	30.2 [b]	1.0	0.72	0.29	0.049	65,400	31.7	21.3	0.72	98	98.80	1.75×10^{-3}	0.12	0.05	0.17	1.0	104	1,678	I
A-30	50.2 [b]	0.995	0.68	0.32	0.048	70,900	34.7	24.4	0.86	29	145.75	2.83×10^{-2}	0.71	0.015	0.72	5.0	29	1906	I

Code: [a] Aged 8760 hours at 400°C. [d] Strain rate $\dot{\epsilon}_s = 4 \times 10^{-3} \text{ sec}^{-1}$.
[b] Fluence $\times 10^{-20} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$ [e] T = transgranular
[c] Aged 3096 hours at 410°C. M = mixed
I = Intergranular

TABLE III
FATIGUE AND CYCLIC DATA FOR TYPE 304 AND 316 STAINLESS (11% COLD WORKED)
TESTED AT 593°C

316 Stainless												
Specimen No.	Condition	$\Delta\epsilon_t$ %	$\Delta\epsilon_p$ %	$\Delta\epsilon_e$ %	$\Delta\sigma$ psi	$\sigma_{t,max}$ ksi	$\sigma_{t,min}$ ksi	N_5/N_f	N_f	t_f ,hr	Tensile Hold Time, hr	Mode of Crack Propagation
E-28	[a]	1.0	0.51	0.49	109,200	54.4	54.4	0.896	1,880	2.60	0	T
E-30	[a]	1.0	0.50	0.50	108,700	53.7	53.7	0.844	2,718	3.74	0	T
E-29	[a]	1.0	0.52	0.48	116,700	57.2	54.1	0.831	1,299	14.87	0.01	T
E-26	[a]	1.0	0.50	0.50	114,700	56.1	52.7	0.658	380	37.7	0.1	I
E-27	[a]	1.0	0.64	0.36	116,200	56.2	42.1	0.429	63	313.0	5.0	I
E-21	44.01[b]	1.0	0.49	0.51	111,000	52.7	52.7	0.895	1,838	2.53	0	T
E-24	2.16[b]	1.0	0.50	0.50	112,100	53.3	50.1	0.795	508	5.76	0.01	I
E-22	15.86[b]	1.0	0.48	0.52	115,000	54.7	48.9	0.936	47	4.77	0.1	I
E-25	1.71[b]	1.0	0.59	0.41	104,900	51.0	39.1	0.678	28	27.83	1.0	I
E-23	4.61[b]	1.0	0.61	0.39	105,800	51.2	36.1	0.666	18	85.20	5.0	I
304 Stainless												
B-21	42.0[b]	1.0	0.54	0.46	88,600	44,000	44,000	0.827	2,813	7.8	0	T
B-23	5.0[b]	1.0	0.61	0.39	83,400	40,800	33,900	0.758	244	24.0	0.1	I
B-29	30.24[b]	1.0	0.60	0.40	75,700	37,400	27,600	0.816	71	71.65	1.0	I

[a] Solution annealed, cold worked 11% by swagging, machined into specimens and aged 8760 hours at 400°C.

[b] Fluence $\times 10^{-20}$ n/cm² E > 1 MeV (450°C).

TABLE IV
CONSTANT STRAIN RATE CYCLIC AND MONOTONIC TENSILE PROPERTIES
OF IRRADIATED AND UNIRRADIATED TYPE 304 AND 316 STAINLESS STEELS
TESTED AT 593°C

Type Test	Specimen No.	Material	Fluence n/cm ² E>0.1 MeV	Stress		Reduction in Area, R.A., %	Fracture Ductility, D ^[f]	Strain Hardening Exponent n	True Fracture Stress, σ_f ksi
				Ultimate, σ_{uts} , ksi	Yield (0.2%), σ_{ys} , ksi				
Monotonic	D-192	316[a]	0	65.64	17.56	62.2	0.972	0.12/0.49[g]	137
Monotonic	D-52	316[b]	0	67.04	23.85	60.3	0.924	0.18/0.46[g]	131
Monotonic	D-27	316[d]	0.5x10 ²¹	66.67	27.42	60.3	0.924	0.14/0.38[g]	93
Cyclic	D-191	316[a]	0	---	44.6	---	---	---	---
Cyclic	D-96	316[c]	0	---	37.5	---	---	---	---
Cyclic	D-28	316[d]	1.2x10 ²¹	---	49.3	---	---	---	---
Monotonic	A-34	304[e]	0	54.65	17.00	68.6	1.160	0.15/0.43[g]	121
Monotonic	A-28	304[d]	1.2x10 ²¹	58.12	45.07	51.0	0.713	0.12	77
Cyclic	A-35	304[e]	0	---	31.5	---	---	---	---
Cyclic	A-23	304[d]	3.5x10 ²¹	---	37.7	---	---	---	---

[a] Solution annealed.

[b] Aged 3096 hours at 410°C.

[c] Aged 3096 hours at 600°C.

[d] Irradiated at 450°C.

[e] Aged 8760 hours at 750°C.

[f] $D = 1n \frac{100}{100-RA\%}$.

[g] First number is for strains up to approximately 0.02 and second number is for strains greater than 0.02.

Fig. 1 Test frame enclosure (atmosphere box).

Fig. 2 Hourglass specimen and extension rods.

Fig. 3 Semiremote loading of specimen and extension rod assembly into electrohydraulic grips.

Fig. 4 Irradiated specimen undergoing fatigue cycling.

Fig. 5 Diametral extensometer, extensometer support and positioning device, and calibration unit.

3. HYSTERESIS LOOP DESCRIPTION AND TEST LENGTH

Subjecting a specimen to a fully reversed push-pull test results in the generation of a closed hysteresis loop each cycle as shown in Figure 6. In cyclic strain controlled tests, the total axial strain range, $\Delta\epsilon_t$, was maintained a constant throughout each test. The internal width of the hysteresis loop with and without hold times is the plastic strain range $\Delta\epsilon_p$. Three different types of hysteresis loops were generated depending on the type of test being conducted: (a) fully reversed without a hold time typified by the solid line in Figure 6, (b) fully reversed with a particular tensile hold time which was repeated each cycle, and during which the stress relaxed from a maximum value of $\sigma_{t,max}$ to a minimum value $\sigma_{t,min}$ as shown by the dashed line in Figure 6, and (c) fully reversed with a compression hold time with relaxation occurring only during the compressive portion of the cycle. $\Delta\epsilon_{cp}$ is the partitioned plastic strain range equal to the amount of elastic strain converted into plastic strain during the tensile hold time and is equal to the difference between $\sigma_{t,max}$ and $\sigma_{t,min}$ divided by the appropriate elastic modulus. The $\sigma_{t,max}$ and $\sigma_{t,min}$ values reported were obtained from stabilized hysteresis loops at approximately half the number cycles to failure ($N_f/2$). Each cyclic test was conducted until complete specimen failure, unless stated otherwise, and the number (N_f) and time (t_f) to failure recorded. In addition, the cycle ration N_5/N_f , (corresponding to the number of cycles to where there had been a 5% decrease in load required to maintain the programmed total axial strain a constant) was also recorded for creep damage calculations.

Fig. 6 Comparison of fatigue hysteresis loops generated with and without a tensile hold time.

III. RESULTS

1. DATA TABULATION

Data obtained from cyclic fatigue and constant strain rate tensile tests are tabulated in Tables I through IV. Cyclic data are presented in Figures 7, 12, and 13 as total time to failure versus the number of cycles to failure.

2. AGING EFFECTS IN UNIRRADIATED TYPE 316 STAINLESS STEEL

Figure 7 compares the cyclic behavior with and without tensile hold times of initially solution annealed or aged Type 316 stainless steel. Isostrain range plots presented in Figure 7 show that increasing the tensile hold time increases the time to failure while decreasing the number of cycles to failure. Pretest aging of the specimens was found to be beneficial in that the number of cycles to failure of the aged material exceeded that of the unaged material. Microscopic examination of fracture surfaces, Figures 8 and 9, indicated that the mode of crack propagation was transgranular for the tests conducted without hold times, but changed to complete intercrystalline propagation for tests with hold times in excess of approximately 0.1 hour for all strain ranges employed, Figure 10. Mixed mode crack propagation occurred for hold times of 0.01 to 0.1 hour. The increased creep-fatigue lifetime of the aged material was probably the result of blocky discontinuous carbide precipitates, Figure 11, observed by transmission electron microscopy, which restricted grain boundary flow or void coalescence^[9,10,11]. Extensive carbide precipitates in stainless steel tested at somewhat lower temperature, however, may not show this beneficial effect^[12].

3. IRRADIATION EFFECTS IN TYPE 304 AND 316 STAINLESS STEEL

In Figure 12, comparisons are made between the behavior of unirradiated solution annealed and aged, and irradiated Type 304 and 316 stainless steel tested at a single strain range of 1%. The data show that for a strain range of 1% the fatigue lives of the unirradiated materials tested are nearly equivalent when no tensile hold time is present. However, when tensile hold times in excess of 0.1 hour are introduced, Type 304 shows the superior creep-fatigue resistance for strain controlled applications. A similar trend was also noted for a strain range of 2% at 650°C^[13]. Data plotted in Figure 12 for the irradiated material tests indicate that irradiation to fluences of 0.3 to 6.0 x 10²¹ n/cm², E > 0.1 MeV (450°C) resulted in a substantial reduction in the creep-fatigue resistance of these stainless steels. Type 304 stainless steel tended to show the greater reduction in creep-fatigue resistance attributable to irradiation after hold times in excess of 0.1 hour; however, Type 304 still tended to show the higher irradiated creep-fatigue resistance.

Fig. 7 Total time to failure versus cycles to failure for Type 316 stainless tested at 593°C (1100°F).

a. Without Tensile Hold Time

b. With a 1hr Tensile Hold Time

←200μ→

Fig. 8 Comparison of the mode of fatigue crack propagation in two specimens of unirradiated 316 stainless steel. $\Delta\epsilon_t = 0.5\%$, $T = 593^\circ\text{C}$ (1100°F).

FIGURE 9.
SCANNING ELECTRON MICROSCOPE FRACTOGRAPHS
SHOWING THE FATIGUED SURFACES OF 316
STAINLESS STEEL TESTED AT A TOTAL
STRAIN RANGE OF 1.0% AT 1100°F.

a. Transcrystalline Failure
Tensile Hold Time=.005
hr.

b. Mixed Mode Failure
Tensile Hold Time=.1 hr.

c. Intercrystalline Failure
Tensile Hold Time=.5 hr.

Fig. 9 Scanning electron microscope fractographs showing the fatigued surfaces of 316 stainless steel tested at a total strain range of 1.0% at 593°C (1100°F).

Fig. 10 Influence of tensile hold times on the fatigue life and mode of fatigue crack propagation in solution annealed and aged Type 316 stainless steel tested 593°C(1100°F).

AGED
(3096 hrs. at 600°C)

ANNEALED

Fig. 11 Transmission electron photo micrographs showing large angle grain boundaries with and without carbide precipitates.

Fig. 12 Total time to failure versus cycles to failure for irradiated and unirradiated 304 and 316 stainless tested at 593°C (1100°F), $\Delta\epsilon_t = 1.0\%$ with several tensile hold times.

4. INFLUENCE OF COLD-WORK

In Figure 13, the results of a number of fatigue and creep-fatigue tests conducted on specimens that had been cold-worked 11% prior to specimen machining are compared with irradiated and unirradiated material position lines obtained from Figure 12. The data show that there was not a significant effect of this amount of cold-work on the unirradiated fatigue and creep-fatigue resistance of Type 316 stainless steel. A similar conclusion can also be drawn from the two irradiated Type 304 stainless steel data points as well. Several of the irradiated data points, however, for Type 316 stainless steel, ie, 0.1, 1.0, and 5.0 hour hold times, fall significantly below the irradiated position line for the non-cold-worked material. This was somewhat surprising in that cold-work has been shown to be beneficial in increasing material resistance to both fatigue^[4,14] and creep (via high dislocation density, and carbide precipitation)^[11,15,16,17]. However, the creep resistance of cold-worked and irradiated materials is complex and is apparently influenced considerably by test temperature, irradiation temperature, and applied stress level^[18].

Fig. 13 Time to failure versus cycles to failure showing the influence of cold-work (C. W.) on the creep-fatigue resistance of irradiated 304 and 316 stainless steel at 593°C (1100°F).

5. STABILIZED STRESS CORRELATIONS

When log-log plots of tensile stabilized stress amplitude, $\sigma_{t,max}$, versus number of cycles to failure were made for all of the tests reported herein, it was found that good correlations using stress could also be made. Test results of aged Type 316 stainless steel, Figure 14, showed a trend toward higher fatigue and creep-fatigue resistance than the solution annealed material, and a corresponding lower stress amplitude. The stress amplitude ($\Delta\sigma/2$) for the aged material remained less than the stress amplitude for the annealed material throughout the test as can be seen from the plots of stress range, $\Delta\sigma$, versus fraction of cycle life, N/N_f , in Figure 15.

Lower stress amplitude was also noted with the aged Type 304 stainless steel when compared to aged Type 316 under identical test conditions. The resultant differences were based on differences in cyclic yield strengths, as given in Table IV. A comparison of the cyclic stress-strain curves are shown in Figure 16. Comparison of data from tests conducted, without tensile hold times, on irradiated and unirradiated material also showed that a higher stress was required to produce a given strain amplitude in the irradiated material. Differences in cyclic stress-strain behavior for the irradiated and unirradiated materials tested are shown in Figure 16. Comparing the stabilized tensile stress amplitudes of a number of tests run at a single strain range showed that increasing tensile hold time resulted in a decrease in the stress amplitude. Comparing the stabilized tensile stress amplitude data tabulated in Tables I and II for the non-cold-worked material, with the data obtained from cold-worked specimens, Table III, it is seen that cold-work increases this value slightly with a resultant small decrease in lifetime.

Fig. 14 Stress amplitude at approximately $N_f/2$ versus total time to failure for Type 316 stainless tested at 593°C (1100°F).

Fig. 15 Stress range versus fraction of fatigue life for annealed and aged 316 stainless tested at 593°C (1100°F).

Fig. 16 Comparison of cyclic and monotonic stress-strain curves as a function of heat treatment and irradiation for Type 304 and 316 stainless steel tested at 593°C (1100°F).

6. STRESS RELAXATION AND DAMAGE SUMMATION

During tensile strain-controlled hold times, constant strain is maintained and the stress changes as a function of time. This is due to the fact that the plastic strain increases with time at the expense of the elastic strain. Since the elastic strain decreases with time the load required to maintain the constant total strain decreases. Plots of average stabilized stress as a function of time during a given hold period are given for a number of the tests reported in Figures 17 and 18.

Fig. 17 Comparison of stress relaxation behavior and damage sums at several strain ranges and tension hold times of 316 stainless fatigued at 593°C (1100°F).

Fig. 1.8 Stress Relaxation.

* Fluence, n/cm^2 , $E > 0.1$ MeV
 --- Irradiated

Fig. 18 (Contd.)

Total Strain Range ($\Delta\epsilon_t$) = 1.0 %
 Total Hold Time (t_h) = 0.01 hour

$\Delta\epsilon_t = 1.0\%$, $t_h = 0.10$ hr

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$\Delta\epsilon_t = 1.0\%$, $t_h = 1.0$ hour

* Fluence, n/cm^2 , $E > 0.1$ MeV
 --- Irradiated

Fig. 18 (Contd.)

Fig. 18 (Contd.)

Currently recommended design practice[19] for high temperature applications involving static and dynamic loading calls for the summation of fatigue and creep damage by a linear rule of the form

$$\sum_{o}^p \frac{N}{N_f} + \sum_{o}^t \frac{\Delta t}{t_r} \leq D \quad (1)$$

where Δt is the incremental time at a stress level σ , t_r is the time to rupture at a stress level σ obtained from appropriate stress rupture curves, N is the number of cycles at a given strain range $\Delta\epsilon_t$, N_f is the time-independent number of cycles to failure for the appropriate strain range, and D is the total damage. It was found that the relation between stress and time during the relaxation period could be defined for both irradiated and unirradiated material by the relation[13]

$$\ln \frac{\sigma_{t,\max}}{\sigma} = \frac{A}{1+M} t^{1+M} \quad (2)$$

where A and M are constants for given strain range, temperature, and hold time and may be computed. Using Equation (2), and replacing the creep damage summation by the integral

$$\int_{o}^t \frac{dt}{t_r} \quad (3)$$

the amount of creep damage that occurred during each cycle was calculated using a simple computer program developed by Campbell[20]. Exponents and coefficients defining the stress-rupture curves for both the irradiated and unirradiated material were calculated from stress-rupture curves found in the literature[21,22]. Creep damage developed during each cycle, as well as an approximation of the total creep damage for an entire test, is tabulated in Tables I and II. The creep damage for a given test is defined as the creep damage obtained for a given cycle in the stress-stabilized range multiplied by N_5 , the number of cycles to a 5% decrease in stabilized stress. Fatigue damage for each test was then calculated and added to the creep damage to form the total damage values tabulated in Tables I and II. Creep, fatigue, and total damage were then recalculated replacing N_f and t_r in Equation (1) by N_d and t_d , where N_d is the design allowable cycles to failure for a given strain range and t_d is the design allowable time at a given stress level according to ASME Code Case 1331-5. Creep damage versus fatigue damage data calculated by the above methods for both irradiated and unirradiated material are plotted in Figure 19. The large data points were calculated using design values while the small data points were calculated using actual failure values of N_f and t_r . Since the values of N_d and t_d are less than the actual fatigue cycles and stress-rupture times to failure, design creep and fatigue damage values are increased by the amounts shown in Figure 19. Restricting the total damage sum to some value of unity or less results in a margin of safety indicated by the displacement of the large data points above the damage lines. The same design criteria were applied to the irradiated and unirradiated material even though the code does not give any guidance with respect to irradiated materials.

Fig. 19 Comparison of creep and fatigue damage values based on actual failure data (t_r , N_f) and ASME Code Case 1331-5 allowable values of t_d and N_d with code allowable damage sums "D" for 304 and 316 stainless steel at 593°C (1100°F), in the irradiated and unirradiated condition.

When comparing the total damage sums it is apparent that creep and fatigue damage do not sum to a unique value, but rather are dependent upon strain range, length of hold time, and material condition. Similar results were reported from a number of tests conducted at 700°C for Type 316 stainless steel^[23]. The dependency of damage fractions on the length of hold times has also been reported for Type 304 stainless steel and Alloy 800^[5,24]. Lagneborg et al^[25], who recently reported on creep-fatigue interaction in 20 pct Cr-35 pct Ni stainless steel subject to reverse bending fatigue at 700°C, similarly found that creep and fatigue damage values did not sum linearly. They employed the nonlinear equation given in Figure 20 to fit their data. The terms given in this equation have the same meaning as defined in Equation (1), where B is a constant. In Figure 20, creep damage is plotted as a function of fatigue damage for unirradiated Type 316 stainless steel. B values were calculated and average values determined for a given strain range as given in Figure 20. As can be seen, the Lagneborg Equation gives a fair fit of the data for a strain range of 1.0% or less; however, at 2.0% strain range the scatter in the data is such that the Lagneborg equation is not appropriate. The point to be made from Figure 20 is that fatigue and creep damage summation values for this material, temperature, and test condition were strain range dependent, and the total damage values, ie, creep plus fatigue, decreased with decreasing strain range.

Fig. 20 Creep damage versus fatigue damage values for unirradiated (aged and annealed) 316 stainless steel tested at 593°C (1100°F). Data fitted with non linear relation to show dependency of damage sum on strain range value.

7. STRAIN RANGE PARTITIONING

Recently, Manson et al[26] suggested that creep and fatigue damage be combined linearly by partitioning inelastic strains produced by plastic flow and creep developed by different methods of fully reversed elevated temperature loading. These strains are then related independently to cycle life, and failure is assumed to occur when the summation of the damage fractions equals unity. For tensile hold time tests this damage summation consists of a fraction associated with plastic flow or pure fatigue and a fraction associated with tensile creep. This summation is written as

$$\frac{N}{N_{pp}} + \frac{N}{N_{cp}} = 1 \quad (4)$$

where N is the number of cycles to failure, N_{pp} is the number of cycles to failure for fully reversed tests run at high enough frequency to avoid strain rate effects, and where the corresponding plastic strain range $\Delta\epsilon_{pp}$ was obtained by plastic flow only in both the tensile and compressive halves of the hysteresis loop. $\Delta\epsilon_{pp}$ is equal to the width of the hysteresis loop, $\Delta\epsilon_p$, shown in Figure 6 for frequency independent tests. N_{cp} is the number of cycles associated with the tensile creep reversed plasticity strain, $\Delta\epsilon_{cp}$ shown in Figure 6. N_{cp} is determined by first measuring N , $\Delta\epsilon_{pp}$, and $\Delta\epsilon_{cp}$ and establishing a relation for N_{pp} . Equation (4) can then be solved for N_{cp} . $\Delta\epsilon_{pp}$ is given by the relation

$$\Delta\epsilon_{pp} = A N_{pp}^{-m} \quad (5)$$

where A and m are constants. $\Delta\epsilon_{cp}$ can then be expressed by a similar relationship

$$\Delta\epsilon_{cp} = A' N_{cp}^{-m'} \quad (6)$$

where A' and m' are again constants. Values of $\Delta\epsilon_{pp}$, $\Delta\epsilon_{cp}$, N_{cp} , and N_{pp} were calculated and are tabulated in Tables I and II. The constants defining Equations (5) and (6) for these materials were calculated and are shown in Figure 21. Thus, for design applications involving closed hysteresis loops of the form shown in Figure 6, it may be possible to estimate the number of cycles to failure using Equations (4), (5), and (6) and the expected inelastic strains.

Fig. 21 Partitioned plastic strain range, tensile creep $\Delta\epsilon_{cp}$ or fatigue $\Delta\epsilon_{pp}$, as a function of cycle life for 304 and 316 stainless tested at 593°C (1100°F).

8. BILINEAR REPRESENTATION OF CYCLICALLY HARDENED STRESS-STRAIN CURVES

The use of a bilinear representation of the cyclically hardened uniaxial stress-strain curve for the kinematic hardening model has recently been recommended by ORNL [27,28]. Since numerous hysteresis loops were generated and recorded during this program, such as those given in Figure 22 for unirradiated material, it was possible to determine the C and κ values defining the bilinear representation, Figure 23, using the following graphical methods:

The value of C, or the slope of the plastic portion of the bilinear curve, monotonic loading, was measured by drawing a straight line connecting two points on

the stress-strain curve, one corresponding to the maximum strain amplitude expected to be encountered and the other point at half this value, Figure 23(a). The value of κ_0 was determined from the point of intersection of the elastic line and the plastic line described above with slope C as shown in Figure 23(a). To obtain κ_1 , the constant defining the 10th hysteresis cycle intersection of the elastic and elastic-plastic line, Figure 23(b), the elastic-plastic slope was first calculated from the relationship, $\frac{3EC}{2(E + \frac{3C}{2})}$, where C is the slope as described above and E is the elastic modulus. Using this calculated slope, a line was drawn at the top and bottom of the hysteresis loop such that the shaded areas shown in Figure 23(b) were approximately equal. The intersection of the elastic line, slope E, and the elastic-plastic lines define κ_1 , as shown in Figure 23(b). For a given material and temperature the cyclic bilinear constants, κ_1 and C are dependent on the total strain range being considered, ie, the two linear portions of the curve change depending on the maximum strain encountered. The data reported herein were generated at total strain ranges of 2.0%, 1.0%, and 0.5% corresponding to maximum strain amplitudes of 1.0%, 0.5%, and 0.25%, respectively. Bilinear constants were calculated using some of the available 593°C (1100°F) data and are tabulated in Table V. These constants were calculated using both Aerojet Nuclear's monotonic tensile data and average monotonic data supplied by HEDL[29]. Any change due to aging is incorporated into the ANC data, but aging effects are unaccounted for when using the LMFBR Materials Handbook (HEDL) tensile data.

It was recommended that the tenth cycle hysteresis loop be used to determine the cyclic bilinear constants; however, it was observed that hardening was not complete, ie, the stress amplitude had not stabilized until some cycle greater than the tenth had been attained, especially in the lower strain ranges as shown in Figure 22. Therefore, the bilinear constant κ_1 was calculated for both the tenth cycle, κ_1 , (or as near to the tenth cycle as had been recorded) and a cycle where the stress had stabilized, κ_s .

Cyclic bilinear constants, κ_c and C_c , were also determined from cyclic tensile test data, Figure 16. Cyclic curves were generated by cycling a single specimen at increasing strain levels in a step-wise fashion maintaining a constant strain rate of $4 \times 10^{-3} \text{ sec}^{-1}$. The strain was increased only after the stress had stabilized. Bilinear constants in this case were measured directly from the cyclic stress-strain curve in an identical fashion to that used for the monotonic curve as shown in Figure 23(a).

A comparison of bilinear constants determined from utilizing Aerojet Nuclear's monotonic tensile data with LMFBR Materials Handbook tensile data revealed that no large deviations existed. However, when the bilinear constants determined directly from cyclic tensile tests are compared to those determined from monotonic data and hysteresis loops, a significant difference is seen. The C_c values (slopes of the plastic region of the stress-strain curve) of the cyclic tests are four to five times greater than the values calculated by the other method, while the κ_1 values from the cyclic tensile tests are lower in comparison.

Fig. 22 Hysteresis loops showing approximately tenth cycle and stress stabilized cycle of unirradiated 304 and 316 stainless steel tested at 593°C (1100°F) and strain ranges of 2.0%, 1.0% and 0.5%.

(a)

(b)

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Fig. 23 Graphic representation for determining bilinear constants as listed in Table V.

TABLE V
BI-LINEAR CYCLIC HARDENING CONSTANTS OF TYPE 304 (Ht. 55697) AND
316 (Ht.65808) STAINLESS STEEL TESTED AT 593°C

Specimen No.	Material & Condition	Total Strain Range, $\Delta\epsilon_t$, %	Based on ANC Tensile Data					Based on LMFBR Materials Handbook Tensile Data				
			Monotonic	Elastic-Plastic Slope [e]	κ_o	10th Cycle κ_l	Stabilized Cycle κ_s	Monotonic Slope, C	Elastic - Plastic Slope [e]	κ_o	10th Cycle κ_l	Cycle κ_s
D-143	316[a]	2.0	3.78 x 10 ⁵	5.526 x 10 ⁵	0.968 x 10 ⁸	5.409 x 10 ⁸	6.88 x 10 ⁸	4.44138 x 10 ⁵	6.4636 x 10 ⁵	1.3561 x 10 ⁸	5.544 x 10 ⁸	7.013 x 10 ⁸
D-139	316[a]	2.0	3.780	5.526	0.968	5.569	7.238	4.44138	6.4636	1.3561	6.187	7.598
D-74	316[a]	2.0	3.780	5.526	0.968	7.591	8.547	4.44138	6.4636	1.3561	7.460	8.547
D-43	316[b]	2.0	6.000	8.641	1.772	5.827	6.010	4.44138	6.4636	1.3561	5.990	6.061
D-79	316[c]	2.0	6.000	8.641	1.771	6.667	7.591	4.44138	6.4636	1.3561	6.792	7.538
D-77	316[c]	2.0	6.000	8.641	1.772	6.349	7.148	4.44138	6.4636	1.3561	6.642	7.433
D-148	316[a]	0.99	3.000	4.405	0.940	2.105	5.250	7.53776	10.7466	1.1862	1.866	5.510
D-150	316[a]	0.5	9.950	13.98	0.832	0.751	1.233	14.56336	19.8468	1.0868	0.119	1.380
D-147	316[a]	0.5	9.950	13.98	0.832	1.148	1.972	14.56336	19.8468	1.0368	1.239	2.194
D-81	316[c]	1.0	11.940	16.54	1.413	1.975	3.645	7.53776	10.7466	1.1862	1.962	3.897
D-78	316[c]	0.51	23.050	29.83	1.167	1.180	1.490	14.56336	19.8468	1.0368	1.088	1.650
A-198	304[a]	2.0	---	---	---	---	---	4.67748	6.7964	1.0911	4.578	5.157
A-71	304[d]	2.0	4.040	5.895	0.946	4.855	5.329	4.67748	6.7964	1.0911	5.038	5.880
A-31	304[a]	1.0	8.880	12.52	0.935	2.325	2.975	8.06368	11.4568	0.9215	2.393	3.174
A-67	304[d]	0.995	7.650	10.89	0.780	2.255	3.090	3.06368	11.4568	0.9215	2.488	3.498
A-73	304[d]	0.51	12.750	17.56	0.679	0.866	1.268	15.36064	20.8290	0.7768	0.856	1.416
A-200	304[a]	0.52	---	---	---	---	---	15.36064	20.8290	0.7768	0.726	1.165

From Cyclic Tensile Tests

Specimen No.	Material & Condition	Total Strain Range, $\Delta\epsilon_t$, %	Cycle Curve Slope, C_c	κ_c	Hold Time, hr
191	316[a]	2.0	25.00 x 10 ⁵	6.07 x 10 ⁸	0
D-191	316[a]	1.0	64.14	2.18	0
D-191	316[a]	0.5	102.20	0.496	0
D-96	316[c]	2.0	26.20	4.27	0
D-96	316[c]	1.0	58.30	1.47	0
D-96	316[c]	0.5	84.20	0.75	0
D-28	316[f]	2.0	24.10	6.98	0
D-28	316[f]	1.0	56.75	3.49	0
D-28	316[f]	0.5	90.06	2.31	0
[g]	316[a]	2.0	18.40	6.25	0.5
[g]	316[a]	2.0	17.40	4.86	5.0
[g]	316[a]	1.0	55.80	2.71	0.5
A-35	304[b]	2.0	21.10	3.10	0
A-35	304[b]	1.0	50.60	0.885	0
A-35	304[b]	0.5	69.20	0.432	0
A-23	304[h]	2.0	17.60	4.15	0
A-23	304[h]	1.0	25.60	3.41	0
A-35	304[h]	0.5	56.40	2.57	0

[a] Annealed.

[b] Aged 8760 hours at 750°C.

[c] Aged 3096 hours at 600°C.

[d] Aged 3096 hours at 410°C.

[e] Elastic-plastic slope = $(3 EC/2)/(E + 3C/2)$.

[f] Irradiated, 1.2×10^{22} n/cm², $E > 0.1$ MeV at 450°C.

[g] Curve generated from several fatigue specimens run at constant strain range.

[h] Irradiated, 3.5×10^{21} n/cm², $E > 0.1$ MeV at 450°C

Some indication of the effect of tensile hold time on the bilinear constants was determined from several fatigue specimens that were run at constant strain ranges with hold times. The effect of hold time is to shift the stress-strain curve downward slightly, and the bilinear constants reflect this shift by slightly reduced κ_1 values.

Two of the specimens subjected to cyclic tensile tests were irradiated; the bilinear constants determined from those tests showed similar values for the elastic-plastic slopes, C_c values, but higher κ_c values in comparison to identical unirradiated test data.

IV. DISCUSSION

1. METHODS OF ESTIMATING LIFETIMES OF MATERIAL SUBJECT TO FATIGUE AND CREEP-FATIGUE INTERACTION

Currently there is a great deal of effort being expended in generating experimental data and in developing the analytical techniques required for predicting long-time material performance of reactor components subject to complex time-dependent loading at elevated temperatures. At the present time, there are a number of techniques which have proven useful in correlating cyclic test data generated by carefully controlled laboratory tests[24,30-32]. However, no single method has yet been selected as a standard method for predicting elevated temperature material performance for the complex stress-strain-time wave forms envisioned. The time to fail versus number of cycles to failure diagram shown in Figures 7, 12, and 13 is one of these methods[24]. In Figures 7 and 12, the isostrain range lines can be represented by a simple power law relation of the form

$$t_f = A N_f^m \quad (7)$$

where A and m are constants for a given strain range, material, temperature, and method of loading. If the time to failure, t_f , is expressed as the sum of the time spent during the hold periods and the time spent in completing the rest of the cycle, Equation (7) can be solved for the number of cycles to failure for any hold time, t_h , that is repeated during the tensile portion of each cycle. This expression is

$$N_f = (1/fA + \frac{t_h}{A})^{\frac{1}{m-1}} \quad (8)$$

where f is the cyclic frequency. Therefore, once the values of A and m have been determined from a number of rather short hold time tests, as are given in Figure 7, an estimate of the number of cycles to failure for longer hold times can be made. Such estimates should be conservative since the hold time effect tends to reach a saturation point, ie, little or no decrease in the number of cycles to failure with increasing length of hold time. This tendency toward saturation is shown for aged Type 304 stainless steel in Figure 12. Figure 12 also shows that the same type of correlation may be possible for irradiated material as well, when more data become available.

Summing fatigue and creep damage linearly using cycles and time at a given stress level as is done when using Equation(1) requires the use of rather large design safety factors, since the damage sums are not unique values but are dependent on material, strain range, and length of hold time. Figure 18 shows, however, that for the unirradiated material data presented herein, that the recommended ASME Code Case 1331-5 method for estimating creep-fatigue behavior should be conservative. However, an additional safety factor will probably have to be employed for applications involving radiation effects.

A method has been proposed for estimating irradiated fatigue properties of materials from a knowledge of the unirradiated strain controlled fatigue properties and the irradiated and unirradiated tensile properties[23,33]. This method is based on a fraction modification of the unirradiated fatigue data defined by the equation

$$\Delta\epsilon_t = \Delta\epsilon_e + \Delta\epsilon_p = AN_f^a + BN_f^b \quad (9)$$

where $\Delta\epsilon_t$ and $\Delta\epsilon_p$ are the elastic and plastic strain ranges and A, B, a, and b are the coefficients and exponents defined by the unirradiated fatigue data. In the absence of pertinent irradiated fatigue data Equation (9) is then modified by making a fractional correction as follows:

$$(\Delta\epsilon_t)_{\text{irrad.}} = \phi_u AN_f^a + \phi_t BN_f^b \quad (10)$$

where

$$\phi_u = \frac{(\sigma_{\text{uts}})_{\text{irrad.}}}{(\sigma_{\text{uts}})_{\text{unirrad.}}} \quad \phi_t = \left[\frac{D_{\text{irrad.}}}{D_{\text{unirrad.}}} \right]^{0.6}$$

σ_{uts} and D, as defined in Table IV, are determined from irradiated and unirradiated tensile tests at the same strain rate and temperature as the unirradiated fatigue tests. Reductions in irradiated fatigue life predicted using this method are compared to experimentally determined reductions for a single strain range of 1% in Table VI. For the limited data available this method gave reduction factors that were equal to or greater (conservative) than the reduction factors measured experimentally. Additional conservatism can be introduced into this method by changing the exponent 0.6 to 1.0. It should be pointed out that this method of estimating fatigue behavior does not take into account hold time or other modes of loading effects and should be considered as only an approximate method at this time.

2. METALLURGICAL AND ENVIRONMENTAL IMPLICATIONS OF THE HOLD TIME EFFECT

The data reported herein, and by other authors, indicate that the ability of a material to resist the deleterious effects of hold times is related to its ability to resist creep damage, ie, low creep rate and resistance to inter-granular crack growth. Comparing the unirradiated data obtained from tests conducted using aged Type 316 stainless steel with that obtained from tests using initially solution annealed material, Figure 7, and comparing the behavior of Types 304 and 316 stainless steel, Figure 12, it is apparent that material metallurgy, eg, phase stability, is an important variable. Tests currently being conducted by Aerojet Nuclear on a number of heats of Type 304 stainless steel, have shown that there can be a considerable heat-to-heat variation in the ability of a given material to resist the hold time effect. This indicates that material thermomechanical history as well as subtle differences in chemistries, eg, carbon and nitrogen^[34] may also be important variables. Other

TABLE VI

ESTIMATES OF IRRADIATION-INDUCED FATIGUE LIFE REDUCTION
FACTORS COMPARED WITH EXPERIMENTALLY DETERMINED
VALUES AT A STRAIN RANGE OF APPROXIMATELY 1% FOR
TYPES 304 AND 316 STAINLESS STEEL

Material	Fluence, n/cm ² E > 0.1 MeV	Temperature Ratio [a] (°C)	Reduction of Area (%)	Ultimate Tensile Strength (ksi)	Fatigue Life Reduction Factor [b]	Data Source
304 stainless	1.2 x 10 ²¹	450/593	51.0	58.22	0.7	Table III
304 stainless	3.8 x 10 ²¹	450/593	[c]	[c]	0.7	Table II
304 stainless	2.9 x 10 ²²	700/700	11.7	38.5	0.3	Ref. 24
304 stainless	1.5 x 10 ²²	700/700	[c]	[c]	0.6	Ref. 24
316 stainless	1.2 x 10 ²²	700/700	22.8	46.0	0.3	Ref. 25
316 stainless	1.8 x 10 ²²	700/700	[c]	[c]	0.4	Ref. 24

[a] Ratio of irradiation temperature to test temperature.

[b] Defined as ratio of irradiated fatigue lifetime to unirradiated fatigue lifetime (approximate value).

[c] By experimental fatigue data comparison

investigators have also shown the importance of environment, primarily oxygen, on the elevated temperature behavior of materials^[35,36]. The interplay and relative importance of environment, metallurgical stability, irradiation effects, and resistance to creep damage in influencing material resistance to frequency and hold time effects over long periods of time is not conclusively known and requires further investigation.

V. CONCLUSIONS

Strain controlled fully reversed fatigue tests with and without tensile hold times were conducted on Types 304 and 316 stainless steel at 593°C (1100°F). From these tests the following conclusions were reached:

(1). Pre-test aging of unirradiated Type 316 stainless steel was found to be beneficial in that fatigue life with and without tensile hold times was improved. Aging resulted in a lower stabilized stress amplitude.

(2). The reduction in fatigue lifetime attributable to the hold time effect increases with decreasing strain range for unirradiated Type 316 stainless steel.

(3). Comparing the resistance to hold time effects of unirradiated Types 304 and 316 stainless steel at a strain range of 1%, it was found that with increasing length of tensile hold time Type 304 stainless steel approached cycle life independent behavior sooner than Type 316 stainless steel, ie, displayed a tendency toward greater creep-fatigue resistance.

(4). Irradiation to fluences of 0.17 to 6.1×10^{21} n/cm², $E > 0.1$ MeV (450°C) resulted in a substantial reduction in the creep-fatigue resistance of these stainless steels.

(5). A pre-test cold-working treatment of 11% did not significantly affect the unirradiated fatigue and creep-fatigue resistance of Type 316 stainless steel. Several of the specimens of Type 316 stainless steel that had been cold-worked and irradiated, however, showed a somewhat lower fatigue life when tested with hold times than irradiated specimens that had not been cold-worked.

(6). Bilinear strain hardening constants which define the cyclically hardened stress-strain curve were determined from hysteresis loops and from cyclic tensile tests. A significant difference between the values obtained by the two methods was found.

(7). It was found that material behavior could be correlated and compared by means of the time to failure versus number of cycles to failure diagram. This method was found useful for estimating tensile creep-fatigue behavior of unirradiated material and may be useful for estimating irradiated material performance as well.

(8). Creep and fatigue damage values were calculated and summed linearly. Damage values were calculated using actual failure data as well as design criteria recommended by ASME Code Case 1331-5. Comparing calculated values of damage sums using design values for cyclic lives and times to failure, and code allowable design damage, it was found that a considerable margin of safety existed for the unirradiated material. Summing creep and fatigue damage linearly, however, does not result in a unique damage value, but one that is strain range, hold time, and material condition dependent.

(9). Inelastic strains developed during the tests were partitioned and relations between strain and the corresponding cycles to failure were given which may permit summation of creep and fatigue damage based on strain.

(10). A method recently proposed for estimating fatigue lifetimes of irradiated material, which uses unirradiated fatigue data and irradiated mechanical properties, was found to give fairly accurate or conservative estimates of actual irradiated material behavior.

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