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TENSILE AND FATIGUE DATA FOR IRRADIATED AND UNIRRADIATED AISI 310 STAINLESS STEEL AND TITANIUM - 5 PERCENT ALUMINUM - 2.5 PERCENT TIN: APPLICATION OF THE METHOD OF UNIVERSAL SLOPES

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16. Abstract

Irradiated and unirradiated tensile and fatigue specimens of AISI 310 stainless steel and Ti-5Al-2.5Sn were tested in the range of 10^2 to 10^4 cycles to failure to determine the applicability of the method of universal slopes to irradiated materials. Specimens were subjected to a fluence of approximately 2×10^{20} neutrons/cm^2 > 1.0 MeV at 340 K. Tensile data for both materials showed a decrease in ductility and increase in ultimate tensile strength due to irradiation. Irradiation caused a maximum change in fatigue life of only 15 to 20 percent for both materials. This suggests that unirradiated data would be sufficient for fatigue life prediction for these materials and conditions. The method of universal slopes predicted all the fatigue data for the 310 SS (irradiated as well as unirradiated) within a life factor of 2. For the titanium alloy 95 percent of the data was predicted within a life factor of 3.

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TENSILE AND FATIGUE DATA FOR IRRADIATED AND UNIRRADIATED AISI 310 STAINLESS STEEL AND TITANIUM - 5 PERCENT ALUMINUM - 2.5 PERCENT TIN: APPLICATION OF THE METHOD OF UNIVERSAL SLOPES

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SUMMARY

AISI 310 stainless steel (310 SS) and titanium - 5-percent aluminum - 2.5-percent tin (Ti5Al-2.5Sn) tensile and fatigue specimens were tested in both the irradiated and unirradiated condition in order to determine the effect of irradiation on the applicability of the method of universal slopes. The irradiated specimens received a fluence of approximately 2×10^{20} neutrons per square centimeter (>1.0 MeV) at 340 K. Fatigue testing was fully reversed and diametrally strain controlled and covered the range of 10^2 to 10^4 cycles to failure. All testing was done at room temperature.

Tensile data for both materials showed a decrease in ductility and increase in ultimate tensile strength due to irradiation. Ductility decreased as much as 25 percent for the titanium alloy and 11 percent for the 310 SS, while ultimate tensile strength increased 6 percent for the titanium and 22 percent for 310 SS.

Fatigue test data results showed that irradiation caused a maximum change in fatigue life of 15 to 20 percent for both materials. This is small when compared with the normal data scatter and suggests that unirradiated data would be sufficient for prediction of irradiated fatigue life for these materials and conditions.

The method of universal slopes predicted all the fatigue data for the 310 SS (irradiated as well as unirradiated) within a life factor of 2. For the titanium alloy, 95 percent of the data were predicted within a life factor of 3.

INTRODUCTION

Portions of structures associated with nuclear reactors may be subjected to stresses high enough to cause cyclic strains beyond the elastic limit. Where such is the case, the low-cycle fatigue properties of the material must be considered when predicting the life of the structure.

Some fatigue and tensile properties of irradiated materials have been determined by others (refs. 1 to 6). There would undoubtedly be more but for the fact that generating fatigue data is costly, particularly when specimens must be irradiated and then tested while radioactive. Much time, money, and effort could be saved, however, if the method of universal slopes correlation (ref. 7) could be applied, since the fatigue life could then be predicted knowing only the results of the standard tensile test. Investigation of the effect of radiation induced property changes on the applicability of the correlation is incomplete however. This problem as it relates to 310 SS and Ti-5Al-2.5Sn at room temperature is the subject of this report. A more extensive effort including other alloys had been planned; however, cancellation of nuclear work at NASA called an early halt to the program.

Sets of both irradiated and unirradiated specimens were tested at the Plum Brook reactor facility. Specimens were irradiated at 340 K to a fast fluence of $\sim 2\times10^{20}$ neutrons per square centimeter (>1 MeV) and a thermal fluence of $\sim 1.5\times10^{21}$ neutrons per square centimeter. All tensile and fatigue tests were run at room temperature. Fatigue tests were diametrally strain controlled with a fully reversed sinusoidal strain versus time history for each cycle. Fatigue life was predicted by the universal slopes correlation. Results of both tensile and fatigue tests are tabulated, and fatigue data are plotted and compared. The applicability of the correlation to irradiated materials is discussed.

SYMBOLS

D	ductility, $\ln \frac{1}{1 - RA}$
E	modulus of elasticity, N/cm^2
N_f	cycles to failure
ΔP	load range, N
RA	reduction in area, percent
$\Delta\Sigma_T^L$	longitudinal total strain range
ϵ_D^T	total diametral deformation, cm
σ_F	failure stress, N/cm^2

σ_u ultimate stress, N/cm^2

σ_y yield stress (0.2 % offset), N/cm^2

EXPERIMENTAL EQUIPMENT

Materials

The materials tested were AISI 310 stainless steel and Ti-5Al-2.5Sn (ELI). They were selected from a group of candidates for NERVA applications. Typical chemical analysis is given in tables I and II. Material condition is given in table III. The 310 SS was of the cyclic strain hardening type, while the titanium alloy was a cyclic strain softening material.

Test Specimens

Specimen configurations are given in figures 1 and 2. The tensile specimens had a gage length to diameter ratio of 4 with a gage diameter of 3.175 millimeters (0.125 in.). To avoid notching, the gage length was delineated by a light sandblasted patch at each end. The fatigue specimens were of the hourglass type with a minimum gage diameter of 5.08 millimeters (0.20 in.). Both types of specimens had threaded ends and both were polished longitudinally to a roughness of 0.203×10^{-9} meter (8 μin.).

Irradiation Capsule

The specimens were irradiated in the LA-5 position of the Plum Brook reactor facility in standard segmented lattice capsules. A typical capsule is shown in figure 3 and is described in reference 8.

TEST APPARATUS

Tensile and fatigue testing was done in the hot cell on typical low-cycle fatigue equipment such as described by Hirschberg (ref. 9). The dieset stiffened load frame (fig. 4) was located in the cell, and the power supply, servosystem, and controls were outside, convenient to the operator. Significant modifications of the equipment were the addition of a Wood's metal grip and a remotely operated wedgelock system. The Wood's metal grip was steam jacketed and bottom mounted; it had three concentric mating surfaces and a load rating of ±454 kilograms. The grip is shown in position in figure 5. The wedgelock system was designed to simplify in-cell specimen mounting by eliminating a difficult threading problem. The system is shown in the locked position in figure 6. In operation the specimen is attached to the female half of the Wood's metal grip and to the upper specimen adapter. This assembly is then mounted in the load frame by sliding the upper adapter into the slot of the grip mounting plate (see fig. 5), thus mating the conical surfaces. Finally the assembly is locked in place by a hydraulically driven wedge.

SPECIMEN INSTRUMENTATION

The servo input signal for the fatigue tests was provided by an Instron diametral strain gage modified by the addition of a pair of aluminum knife edges. Tensile tests were run with two transducers in order to cover the strain range. A Lockheed extensometer using a linear variable differential transformer (LVDT; see ref. 10) provided the input signal through the 0.2 percent offset. Then, from that point to failure, the signal was provided by the load frame actuator LVDT.

PROCEDURE

Irradiation

Six tensile and eighteen fatigue specimens were irradiated for each of the two materials. An identical set of unirradiated specimens were soaked in reactor primary water for use as controls. This gave a total of 96 specimens in the program.

The 48 specimens to be irradiated were loaded into 2 capsules (fig. 3), 24 in each, 6 to a segment. Each capsule was then irradiated serially for two reactor cycles. A 180° rotation between cycles was necessary to compensate for the radial flux gradient. A fluence of approximately 1.9×10^{20} neutrons per square centimeter (>1 MeV) was desired. Actual fluence values were calculated from nickel and cobalt flux wires, which were irradiated along with the specimens. These values are given in table IV.

Control Specimens

Identical sets of unirradiated control specimens (6 tensile, 18 fatigue) were soaked in deionized water at 366 K (200° F). Soaking time equalled the reactor test time of the irradiated specimens in order to expose (insofar as possible) all specimens to a similar corrosive environment.

Testing

All tensile and fatigue testing was done at room temperature in the hot cell. Standard ASTM practices were used wherever possible. The maximum strain rate for the tensile tests did not exceed 3.33×10^{-4} second^{-1}. All fatigue specimens were tested at zero mean strain at a rate of 0.25 hertz. Cyclic input wave form was sinusoidal and approximately 15 cycles were used to ramp the strain to the test value.

RESULTS AND DISCUSSION

Tensile Data

Tensile data are summarized in tables V and VI. The effect of irradiation on the tensile properties of the two materials is shown in table VII. Percent changes are referred to the unirradiated state. Irradiation caused an increase in the yield and ultimate strengths and a decrease in ductility (reduction in area). The yield strength increased at a greater rate than the ultimate, giving a corresponding increase in the σ_y/σ_u ratio. Fracture strength decreased in the titanium alloy, but no significant change was observed in the 310 SS. Significant changes in the ductility of the titanium alloy and ultimate yield strengths of 310 SS were observed. The fluence ($\sim2\times10^{20}$ neutrons/cm^2 > 1 MeV) had little effect on the value of Young's modulus for both materials, on the ultimate strength for the titanium alloy, and on the ductility for 310 SS.

Fatigue Data

Fatigue data are summarized in tables VIII and IX Longitudinal strain range as a function of fatigue life is plotted for the unirradiated and irradiated states of both materials in figures 7 to 10. The solid lines in these figures represent the predicted values based on either the unirradiated or irradiated tensile data and were constructed according to reference 1. The dashed lines represent the measured data. Predicted life as a function of measured life for 310 SS and the titanium alloy is shown in figures 11 and 12.

Looking at the effect of irradiation on fatigue life (i.e., the shift in the dashed line of figs. 7 to 10 from the unirradiated to irradiated states), both materials were only slightly affected. Irradiation caused a small increase in life for 310 SS in the high strain ranges and hardly any change in the low strain range. Titanium behaved in the opposite manner in the high strain area showing a small decrease in life but still showed no change in the high strain range. Maximum deviation for both materials was about 20 percent

The degree of correlation achieved by the method of universal slopes for both irradiated and unirradiated states is indicated in figures 11 and 12. The 45° line through the origin represents perfect correlation. In general, measured life exceeded predicted life for both materials with 310 SS correlating much better than the titanium alloy. Specifically, all of the fatigue life data for 310 SS correlates within a factor of 2. For the titanium alloy 95 percent of the data correlates within a factor of 3.

CONCLUDING REMARKS

The testing of the two materials of this report was the beginning of a broader investigation. However, the cancellation of the NERVA program and cessation of nuclear research by NASA terminated testing at this point. The data are therefore incomplete. One very general observation can be made, however: The effect of irradiation on the fatigue life of the two materials is really insignificant when one takes into consideration the fact that a deviation by a factor of 2 from the universal slopes prediction is not unusual. It appears, therefore, that irradiated fatigue data are unnecessary and that unirradiated data can be used when considering these materials for exposures up to 2×10^{20} neutrons per square centimeter (>1 MeV).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 20, 1973,
503-25.

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TABLE I. - AISI 310 STAINLESS STEEL

CHEMICAL ANALYSIS

Element	Content, wt. %	Element	Content, wt. %
Carbon	0.038	Molybdenum	0.180
Manganese	1.600	Copper	.190
Silicon	.680	Cobalt	.076
Phosphorus	.018	Nitrogen	.042
Sulphur	.007	Tin	.005
Chromium	25.080	Lead	<.001
Nickel	20.710	Silver	<.001

TABLE II. - Ti-5Al-2.5Sn

CHEMICAL ANALYSIS

Element	Content	
	wt. %	at. %
Iron	0.028	-----
Aluminum	5.430	-----
Tin	2.410	-----
Carbon	.033	0.130
Nitrogen	.011	.040
Hydrogen	.006	.290
Oxygen	.053	.160

TABLE III. - CONDITIONING OF MATERIAL

Material	Conditioning
AISI 310 SS	15 min at 1040° C; water quench; hardness (Rockwell B), 76 to 77
Ti-5Al-2.5Sn (ELI)	Annealed; TMCA[a] specification 49021-1; hardness (Rockwell C), 24.9

[a]Titanium Metals Corporation of America.

TABLE IV. - FAST AND THERMAL FLUENCE

Specimens	Thermal fluence, neutrons/cm^2	Fast fluence, neutrons/cm^2 > 1 MeV
AISI 310 stainless steel		
[a]102 - 106	1.5×10^{21}	1.63×10^{20}
401 - 406	1.16	1.31
407 - 412	1.31	1.54
413 - 418	1.42	1.63
Ti-5Al-2.5Sn		
201 - 206	1.44×10^{21}	2.09×10^{20}
401 - 406	1.18	1.89
407 - 412	1.31	2.18
413 - 418	1.39	2.27

[a]Only five specimens tested.

TABLE V. - TENSILE DATA FOR Ti-5Al-2.5Sn

(a) Unirradiated

Specimen	Modulus of elasticity, E, N/cm^2	Yield stress, σ_y, N/cm^2	Ultimate stress, σ_u, N/cm^2	Stress ratio, σ_y/σ_u	Reduction in area, %	Failure stress, σ_F, N/cm^2
212	1.28×10^7	7.03×10^4	7.93×10^4	0.89	46	11.2×10^4
211	1.26	7.19	8.29	.87	44	12.5
210	1.25	7.36	8.37	.88	43	12.3
209	1.22	7.87	8.59	1.13	43	12.5
208	1.05	7.79	8.29	.94	44	N/A
207	1.17	7.31	7.93	.92	46	11.4

(b) Irradiated

Specimen	Modulus of elasticity, E, N/cm^2	Yield stress, σ_y, N/cm^2	Ultimate stress, σ_u, N/cm^2	Stress ratio, σ_y/σ_u	Reduction in area, %	Failure stress, σ_F, N/cm^2
206	1.32×10^7	8.30×10^4	8.24×10^4	1.00	38	10.7×10^4
205	1.36	8.69	8.93	.97	33	10.9
204	1.32	8.33	8.62	.97	35	11.4
203	1.25	8.67	8.73	.99	33	11.1
202	1.39	8.76	8.87	.99	36	11.6
201	1.39	8.71	8.65	1.0	37	11.5

TABLE VI. - TENSILE DATA FOR AISI 310 STAINLESS STEEL

(a) Unirradiated

Specimen	Modulus of elasticity, E, N/cm^2	Yield stress, σ_y, N/cm^2	Ultimate stress, σ_u, N/cm^2	Stress ratio, σ_y/σ_u	Reduction in area, %	Failure stress, σ_F, N/cm^2
107	2.59×10^7	4.59×10^4	5.98×10^4	0.77	81	NA[a]
108	1.77	5.19	5.98	.87	78	2.25×10^4
109	2.11	4.99	6.03	.83	79	1.83
110	2.02	4.69	5.99	.78	80	1.89
111	1.83	4.76	5.99	.79	80	1.84
112	2.14	4.71	6.14	.77	79	1.79

(b) Irradiated

102	2.16×10^7	6.94×10^4	7.88×10^4	0.98	78	1.96×10^4
103	2.43	7.52	7.52	1.0	74	1.89
104	2.21	7.22	7.25	.99	75	1.85
105	1.93	7.17	7.17	1.0	75	1.77
106	2.72	7.96	7.72	.99	75	2.10

[a]Not available.

TABLE VII. - EFFECT OF IRRADIATION ON TENSILE PROPERTIES

[Fluence, $\sim1.9\times10^{20}$ neutrons/cm^2 > 1 MeV; all average values.]

(a) Ti-5Al-2.5Sn

Tensile property	Unirradiated	Irradiated	Difference	Percent change
Modulus of elasticity, E, N/cm^2	1.21×10^7	1.34×10^7	0.13×10^7	11
D	0.579	0.435	-0.144	-25
Ultimate stress, σ_u, N/cm^2	8.2×10^4	8.7×10^4	0.5×10^4	6
Yield stress, σ_y, N/cm^2	7.7×10^4	8.5×10^4	0.8×10^4	11

(b) AISI 310 stainless steel

Modulus of elasticity, E, N/cm^2	2.07×10^7	2.22×10^7	0.15×10^7	7
D	1.58	1.41	-0.17	-11
Ultimate stress, σ_u, N/cm^2	6.02×10^4	7.3×10^4	1.28×10^4	22
Yield stress, σ_y, N/cm^2	4.83×10^4	7.3×10^4	2.47×10^4	51

TABLE VIII. - FATIGUE DATA FOR Ti-5Al-2.5Sn

(a) Unirradiated

Specimen	Total diametral deformation, ϵ_D^T, cm	Load range, ΔP N	Cycles to failure, N_f	Longitudinal total strain range, $\Delta \Sigma_T^L$
419	7.62×10^{-3}	2.836×10^{4}	617	3.44×10^{-2}
420	12.70	3.036	196	5.47
421	5.58	2.769	970	2.63
422	17.70	3.225	93	7.50
423	17.70	3.192	155	7.50
424	17.70	3.192	140	7.50
425	12.70	3.180	151	5.49
426	12.70	3.114	185	5.48
427	7.62	2.991	805	3.46
428	3.86	2.736	2 584	1.94
429	3.86	2.691	2 365	1.94
430	2.29	2.459	10 895	1.28
431	7.62	2.936	865	3.46
432	5.59	2.802	1 189	2.64
433	5.59	2.825	1 259	2.64
434	2.24	2.447	7 727	1.26
435	2.29	2.402	10 246	1.27
436	5.08	2.847	2 132	2.44

(b) Irradiated

401	15.20×10^{-3}	3.025×10^{4}	201	6.36×10^{-2}
402	15.20	3.069	172	6.36
403	15.20	3.025	202	6.36
404	10.60	3.025	265	4.56
405	10.60	3.025	307	4.56
406	10.60	3.025	197	4.56
407	7.11	2.847	764	3.14
[a]408	----------	---------	------	---------
409	7.11	2.891	708	3.14
410	4.83	2.802	1 768	2.23
411	5.08	2.758	2 304	2.33
412	5.08	2.758	1 561	2.33
413	3.56	2.599	3 258	1.71
414	3.56	2.758	2 574	1.73
415	3.56	2.758	2 010	1.73
416	2.03	2.269	10 473	1.07
417	2.03	2.535	8 355	1.09
418	2.03	2.269	14 537	1.07

[a]Not tested.

TABLE IX. - FATIGUE DATA FOR AISI 310 STAINLESS STEEL

(a) Unirradiated

Specimen	Total diametral deformation, ϵ_D^T, cm	Load range, ΔP, N	Cycles to failure, N_f	Longitudinal total strain range, $\Delta\Sigma_T^L$
419	12.70×10^{-3}	2.660×10^{4}	315	5.25×10^{-2}
420	12.70	2.579	321	5.25
421	12.70	2.633	327	5.25
422	2.29	1.690	10 000	1.06
423	7.62	2.553	849	3.24
424	7.62	2.379	940	3.24
425	15.20	2.668	210	6.25
426	20.30	2.936	141	8.28
427	30.50	3.336	59	12.30
428	2.54	1.646	7 625	1.16
429	2.54	1.690	9 484	1.16
430	5.08	2.184	1 711	2.02
431	5.08	2.535	1 090	2.24
432	6.35	2.482	912	2.74
433	7.62	2.638	598	3.25
[a]434	----------	---------	------	----------
435	5.08	2.028	2 499	2.19
[a]436	----------	---------	------	----------

(b) Irradiated

Specimen	Total diametral deformation, ϵ_D^T, cm	Load range, ΔP, N	Cycles to failure, N_f	Longitudinal total strain range, $\Delta\Sigma_T^L$
401	27.90×10^{-3}	3.114×10^{4}	97	11.28×10^{-2}
402	27.90	3.025	98	11.27
403	27.90	3.069	103	11.27
404	18.80	2.891	198	7.66
405	18.80	2.891	152	7.66
406	18.80	2.936	174	7.66
407	11.70	2.691	323	4.84
408	11.70	2.758	381	4.84
409	11.70	2.669	520	4.84
410	7.62	2.579	945	3.23
411	7.62	2.402	656	3.21
412	7.62	2.313	1 116	3.20
413	4.57	2.033	2 847	1.98
[a]414	----------	---------	------	----------
[a]415	----------	---------	------	----------
[a]416	----------	---------	------	----------
417	2.29	1.957	8 970	1.07
418	2.29	1.868	11 871	1.07

[a]Not tested.

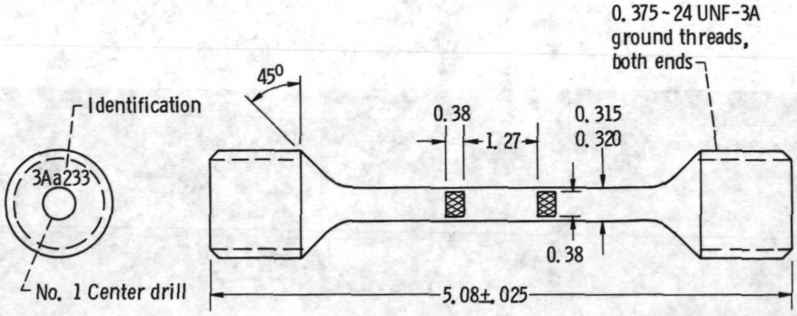

Figure 1. - Miniature tensile specimen. (All dimensions are in cm.)

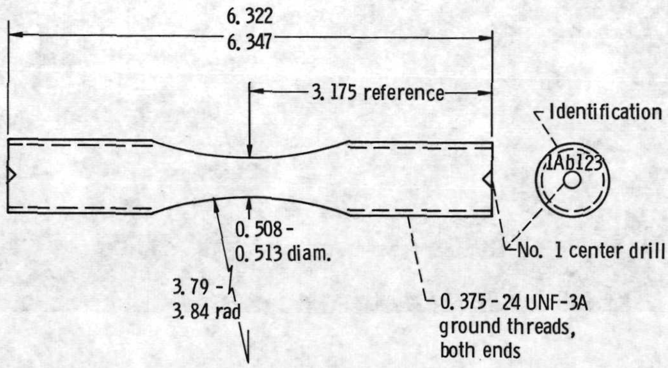

Figure 2. - Hourglass fatigue specimen. (All dimensions in cm.)

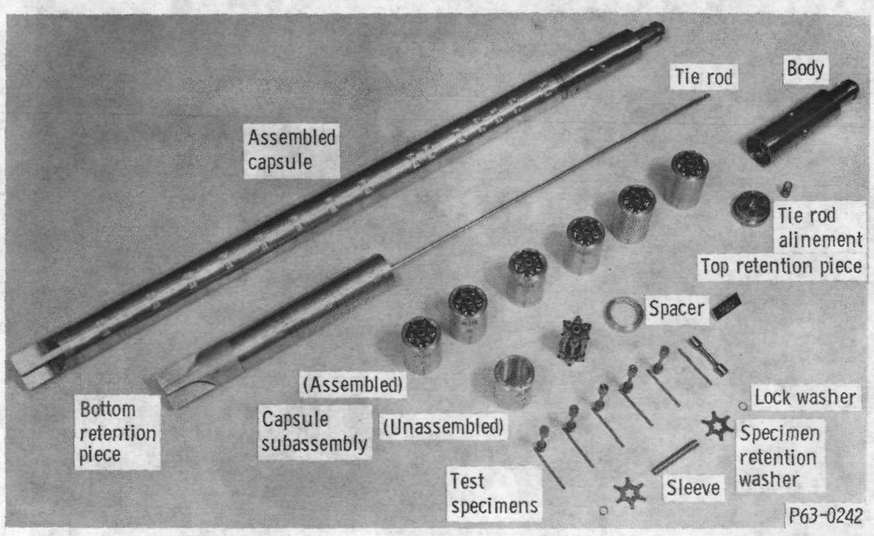

Figure 3. - LA capsule.

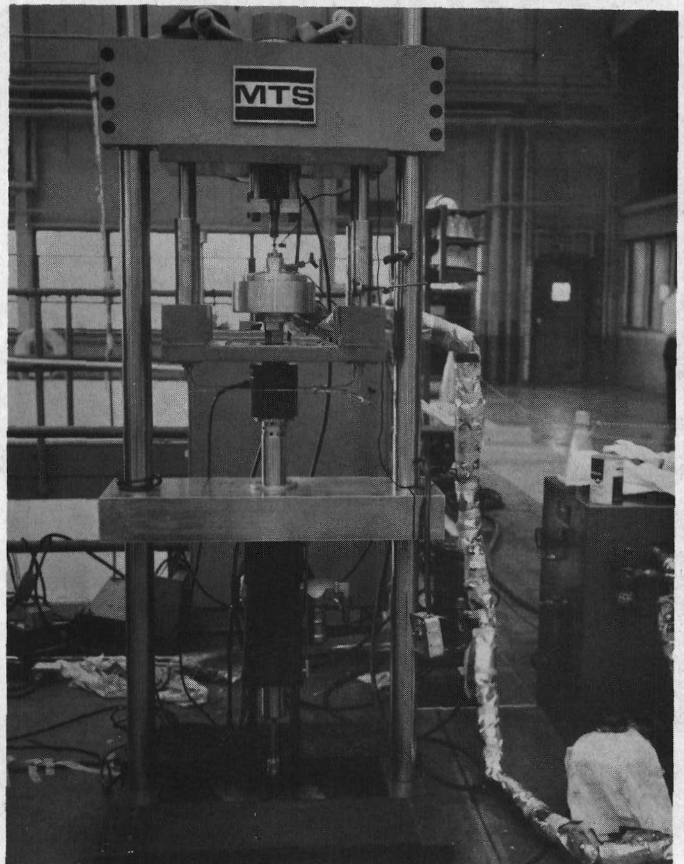

Figure 4. - Overall view of test system.

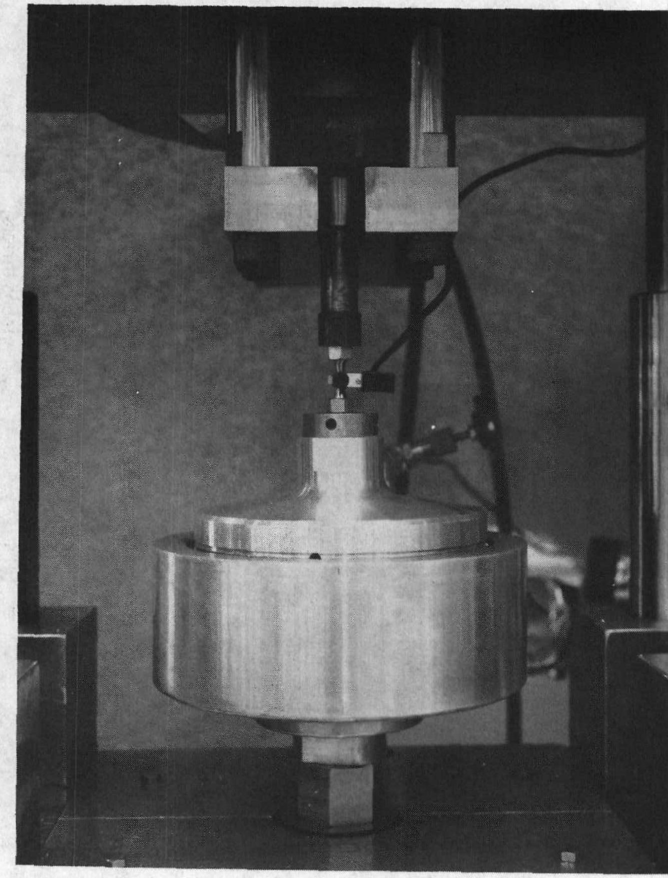

Figure 5. - Wedgelock and Wood's metal grip with specimen in place.

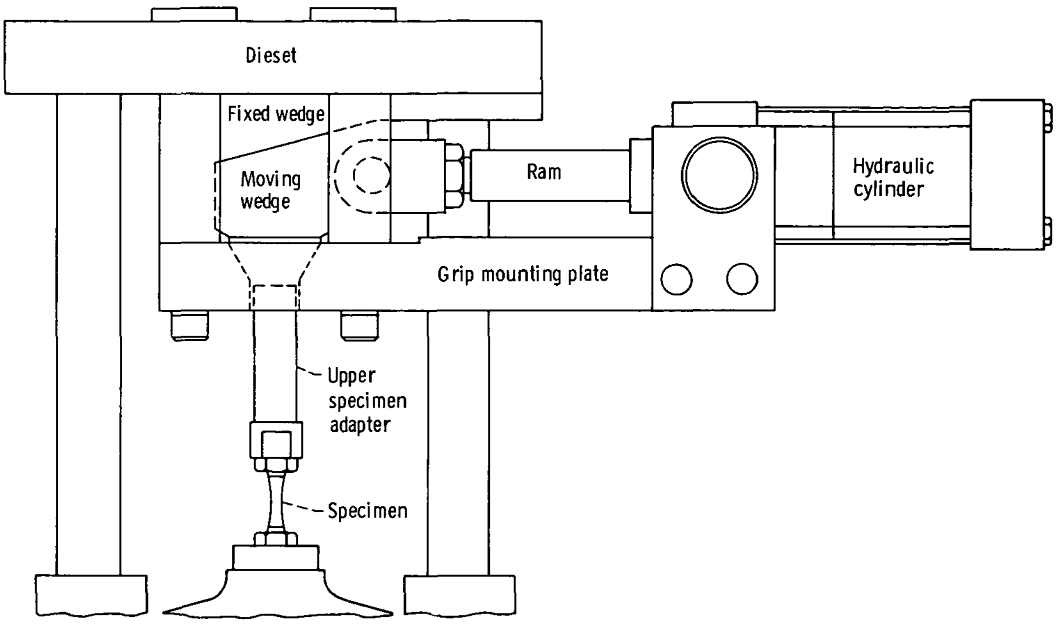

Figure 6. - Wedgelock system.

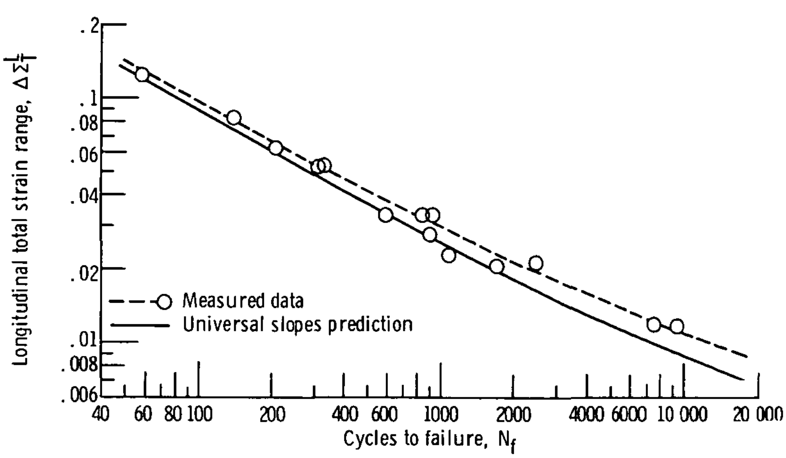

Figure 7. - Longitudinal total strain range as function of cycles to failure for unirradiated AISI 310 stainless steel.

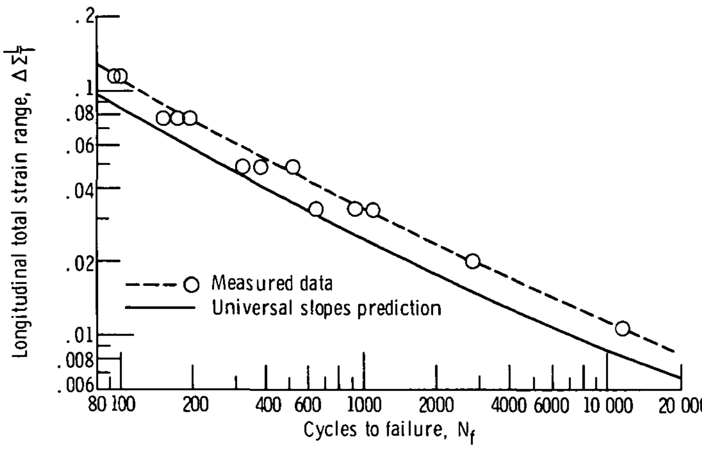

Figure 8. - Longitudinal total strain range as function of cycles to failure for irradiated AISI 310 stainless steel.

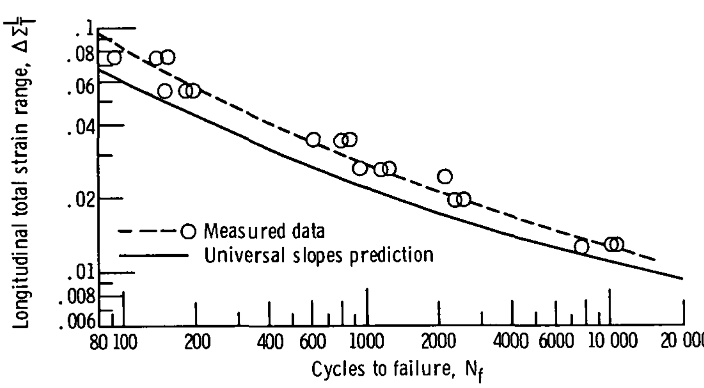

Figure 9. - Longitudinal total strain range as function of cycles to failure for unirradiated Ti-5Al-2.5Sn.

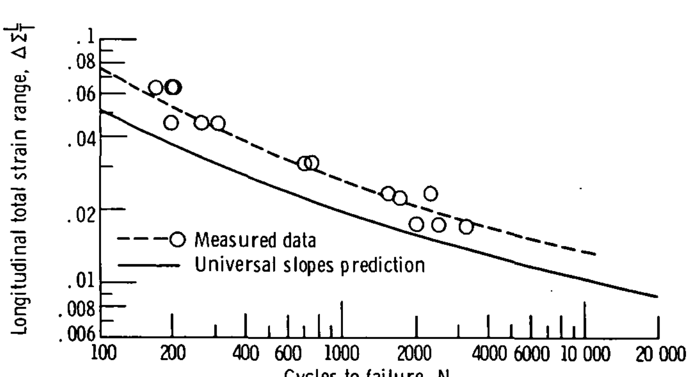

Figure 10. - Longitudinal total strain range as function of cycles to failure for irradiated Ti-5Al-2.5Sn.

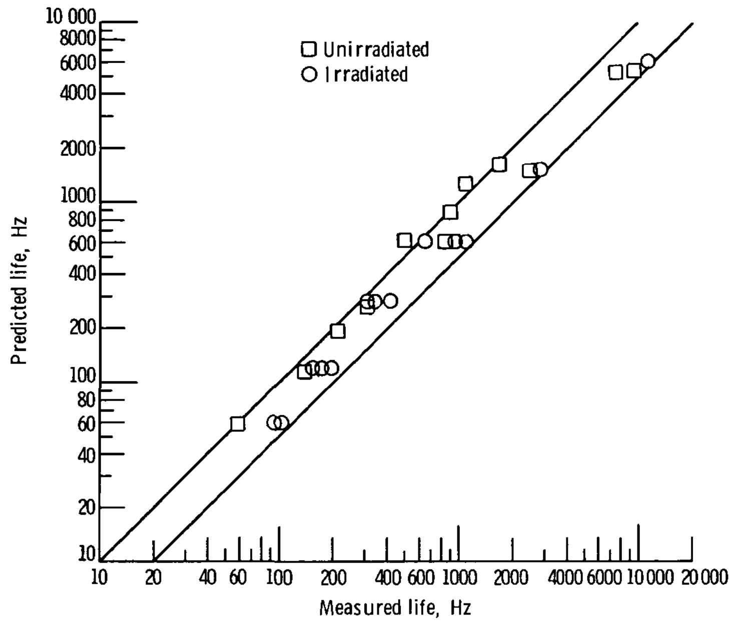

Figure 11. - Degree of universal slopes correlation for AISI 310 stainless steel.

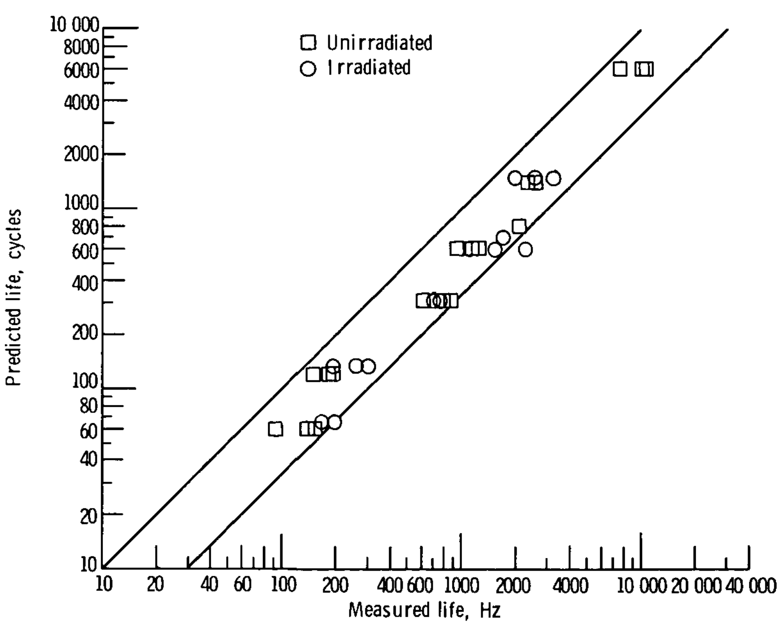

Figure 12. - Degree of universal slopes correlation for Ti-5Al-2.5Sn.

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