T107SNA--2075

AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

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TO: R. G. Ackerman DATE: 18 October 1971
N8200:M3053:AJM:jak

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SUBJECT: Statistical Analysis of 347 Stainless Steel
and Hastelloy-X Fatigue Test Results

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ENCLOSURE: (1) Fatigue Test Data for Type 347 Stainless Steel
(2) Fatigue Test Data for Hastelloy-X
(3) Summarized Results of the Analysis - 347 Stainless
Steel
(4) Summarized Results of the Analysis - Hastelloy-X

PURPOSE OF THE ANALYSIS

MASTER

A series of fatigue tests were performed on specimens of 347 stainless steel and Hastelloy-X at three temperature levels: 1000°F, 1400°F, and 1600°F. The purpose of the statistical analysis of the resultant test data was to develop estimates of the relationships between total axial strain and the fatigue life (in terms of cycles to failure) at each of the three temperature levels for both materials. In addition, of interest were the corresponding 99/95 limits (numbers of cycles which 99% of the specimens exposed to a fixed strain level could be expected to survive with a confidence level of .95).

SUMMARY OF RESULTS

The results of the statistical analysis, Enclosures (3) and (4), indicate that the relationships between log percent total strain and log fatigue life could be adequately represented by straight lines in all cases except one (at 1000°F the 347 stainless steel results were found to be best represented by a quadratic relationship between log percent total strain and log fatigue life). At the two lower temperature levels (1000°F and 1400°F) the 347 stainless steel specimen generally exhibited longer fatigue lives than the Hastelloy-X specimens both in terms of mean expected life and 99/95 life. At the 1600°F temperature level, however, the two materials exhibited essentially equivalent mean lives while the Hastelloy-X specimens exhibited slightly higher 99/95 lives.

In these calculations heat-to-heat variations were treated as a random variable. Under this assumption the 347 stainless steel results were felt

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18 October 1971

to satisfy the T.D. 69-28 and T.D. 69-37 requirements for Class A material data at all three temperature levels. The Hastelloy-X results satisfied the Class A data requirements at the 1000°F and 1600°F levels but not at the 1400°F level. With reference to these conclusions, it should be noted that there is a lack of clear agreement at the present time on the precise interpretation of the material data classifications, especially as they apply to fatigue test data. As a result these conclusions are subject to change if changes in interpretation occur.

METHOD OF ANALYSIS

The fatigue test data which served as the basis of the analysis is presented in Enclosures (1) and (2). Three heats of material (designated as A, B, and C) were available for 347 stainless steel while only two heats (designated as D and E) were available for Hastelloy-X. The test results consisted of the fatigue lives (in terms of cycles-to-failure) observed at various applied levels of percent total strain.

Plots of the data indicated that in all cases except one the relationship between log fatigue life and log strain level was reasonably linear. The exception was the 347 stainless steel results at 1000°F where there was sufficient non-linearity in the data to justify a second order (quadratic) model to express the relationship between log fatigue life and log strain level.

Regression analyses were performed at each of the temperature levels for each of the heats of the two materials. These analyses were performed using the G.E. Mark I library program MULFTS***, which provides least squares fits to sets of data and the associated means and variances.

The remainder of the analysis was performed using methods described in R101-NRP-502, Sampling for Fatigue Test. The methods described in this procedure consist essentially of the following steps:

For a given material at a defined temperature level,

1. For each heat, develop a curve fit to log fatigue life (N_f) vs log percent strain level (s).
2. Pooling the results of the individual heats.
 - (a) Develop an overall relationship between log N_f and log s.
 - (b) Develop an overall estimate of within heat variation, $\hat{\sigma}_W^2$.
3. Estimate the heat-to-heat variation, $\hat{\sigma}_L^2$.
4. Calculate the combined variation, $\hat{\sigma}^2$, of $\hat{\sigma}_W^2$ and $\hat{\sigma}_L^2$.

5. Calculate the degrees of freedom, f , associated with $\hat{\sigma}^2$.
6. For each strain level of interest,
 - (a) Calculate the log expected (or mean) fatigue life using the fitted equation relating log fatigue life and log strain.
 - (b) Calculate the effective sample size, n_e , associated with the strain level.
 - (c) Determine the tolerance factor, K , associated with the values of $P = .99$, $\gamma = .95$, n_e and f from appropriate tables or using the G.E. Mark II program TFAC**.
 - (d) Calculate the log of the lower 99/95 limit as follows:
$$\log 99/95 \text{ limit} = \log \text{ expected life} - K\hat{\sigma}$$
 - (e) Take the antilog of the log 99/95 limit to determine the lower 99/95 limit on fatigue life at the specified strain level of interest.

The above procedure was followed for each of the materials at each of the temperature levels. The results of the calculations are presented in Enclosures (3) and (4). Although desirable, no combining (pooling) of results among the several temperature levels of a material was possible, due to the highly dissimilar results observed at the several temperature levels.

Technical Directives 69-28 and 69-37 provide the rules and criteria to be used in the classification of materials data into various categories, e.g., A, B, C, D. Unfortunately, following the implementation of the directives, many questions have arisen with respect to their intent and interpretation. For example, it is not clear whether or not lot-to-lot variation should be considered as a part of the random variation, nor is it clear how the directives apply to fatigue data analyses, etc. These problems are currently being investigated by ANSC and SNSO-C representatives. As a result of these questions there is no clear cut answer with respect to the proper classification of the results of the subject analyses.

If the lot-to-lot variation is treated as a random source of variation, then all of the 347 stainless steel results satisfy the requirements of Technical Directives 69-28 and 69-37 with respect to "A" data. This conclusion is also based on the assumption that normal regression analysis techniques can be utilized to estimate the effective sample size at each strain level (an assumption with no clear direction from T.D. 69-28). The results for Hastelloy-X, however, satisfy the criteria of T.D. 69-28 with respect to "A" data only at the 1000°F and 1600°F levels. The 1400°F results should be classified at some lesser material category.

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FATIGUE TEST DATA FOR TYPE 347 STAINLESS STEEL

1000°F

HEAT A		HEAT (B)		HEAT C	
CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN
132	4.92	124	4.94	155	4.93
170	4.97	142	4.94	164	4.93
172	4.89	150	4.92	174	4.92
300	2.92	327	2.91	336	2.95
401	2.92	339	2.92	372	2.91
403	2.96	405	2.89	397	2.92
1856	1.49	1590	1.48	1369	1.50
1975	1.48	1877	1.38	1952	1.49
2251	1.46	2536	1.39	2443	1.47

FATIGUE TEST DATA FOR TYPE 347 STAINLESS STEEL

1400°F

HEAT A		HEAT B		HEAT C	
CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN
113	4.89	102	4.88	111	4.92
119	4.88	150	4.88	135	4.87
168	4.89	162	4.87	191	4.85
214	2.96	162	2.94	238	2.95
280	2.96	258	2.94	299	2.95
286	2.94	260	2.95	368	2.95
677	1.49	648	1.49	796	1.46
691	1.49	739	1.49	822	1.49
700	1.45	790	1.50	950	1.50
820	1.49				

FATIGUE TEST DATA FOR TYPE 347 STAINLESS STEEL

1600°F

HEAT A		HEAT B		HEAT C	
CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN
356	4.97 ✓	359	4.96	767	1.70
2111	1.28 ✓	479	2.97	1889	1.48
754	2.98	2245	1.48	139	5.12
2000	1.44	517	2.94	482	4.95
1821	1.47	232	3.00	1522	1.50
241	4.97	294	5.30	190	5.32
178	4.93	151	4.96	1913	1.45
437	3.20	2124	1.5	553	2.94
446	2.96	2545	1.44	479	2.94
		2850	1.48	516	2.94

FATIGUE TEST DATA FOR HASTELLOY-X

1000°F

HEAT D		HEAT E	
CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN
56	4.73	30	4.90
56	5.04	51	4.85
81	5.02	98	4.75
93	4.95	104	4.86
179	3.02	104	4.96
212	3.01	194	2.95
240	2.96	238	2.94
328	3.00	241	3.00
1029	1.50	289	2.96
1315	1.45	846	1.49
1775	1.26	1589	1.50
2205	1.46	1644	1.50
4750	1.21	2193	1.40

FATIGUE TEST DATA FOR HASTELLOY-X

1400°F

HEAT D		HEAT E	
CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN
99	4.92	50	4.91
108	4.88	59	4.89
136	4.93	61	4.92
137	4.88	67	4.92
203	2.96	228	2.92
230	2.96	262	2.84
251	2.98	275	2.92
283	2.94	314	2.93
865	1.47	629	1.45
923	1.50	708	1.48
929	1.47	720	1.47
964	1.47	935	1.44

FATIGUE TEST DATA FOR HASTELLOY-X

1600°F

HEAT D		HEAT E	
CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN	CYCLES TO FAILURE N_f	PERCENT TOTAL STRAIN
129	6.64	2278	1.51
227	3.95	596	2.96
784	1.96	185	5.01
1731	1.53	194	4.97
469	3.00	479	3.00
522	2.95	1998	1.53
2283	1.48	219	4.96
473	3.00	172	5.27
277	4.96	425	3.00
193	5.01	981	1.65
1805	1.59	301	3.34
1601	1.49		
185	5.19		
255	4.95		
2249	1.51		
621	2.96		

SUMMARIZED RESULTS OF THE ANALYSIS

TYPE 347 STAINLESS STEEL

BEST FIT TREND LINES*

1000°F

HEAT A:	$\text{Log } N_f = 8.89237 - 3.56974 \text{ Log } s + .73028 (\text{Log } s)^2$
HEAT B:	$\text{Log } N_f = 8.59799 - 3.08173 \text{ Log } s + .490895 (\text{Log } s)^2$
HEAT C:	$\text{Log } N_f = 8.80809 - 3.4971 \text{ Log } s + .7357 (\text{Log } s)^2$
COMBINED:	$\text{Log } N_f = 8.76615 - 3.38286 \text{ Log } s + .652278 (\text{Log } s)^2$

1400°F

HEAT A:	$\text{Log } N_f = 7.13058 - 1.43088 \text{ Log } s$ ✓
HEAT B:	$\text{Log } N_f = 7.09576 - 1.43405 \text{ Log } s$
HEAT C:	$\text{Log } N_f = 7.33845 - 1.50819 \text{ Log } s$
COMBINED:	$\text{Log } N_f = 7.18620 - 1.45675 \text{ Log } s$

1600°F

HEAT A:	$\text{Log } N_f = 8.11979 - 1.63778 \text{ Log } s$
HEAT B:	$\text{Log } N_f = 8.40969 - 1.90621 \text{ Log } s$
HEAT C:	$\text{Log } N_f = 7.93392 - 1.54246 \text{ Log } s$
COMBINED:	$\text{Log } N_f = 8.155662 - 1.697473 \text{ Log } s$

* s = Percent total strain. All log values are Log_e .

SUMMARIZED RESULTS OF THE ANALYSIS
TYPE 347 STAINLESS STEEL

PERCENT TOTAL STRAIN	1000°F			1400°F			1600°F		
	EFFECTIVE	EXPECTED LIFE (CYCLES)	LOWER 99/95 LIMIT (CYCLES) ²	EFFECTIVE	EXPECTED LIFE (CYCLES)	LOWER 99/95 LIMIT (CYCLES) ²	EFFECTIVE	EXPECTED LIFE (CYCLES)	LOWER 99/95 LIMIT (CYCLES) ³
	SAMPLE SIZE n _e			SAMPLE SIZE n _e			SAMPLE SIZE n _e		
5.0	11	150	94	8	127	64	11	227	70
4.5	13	173	108	9	148	75	14	271	85
4.0	17	206	130	12	175	90	18	331	105
3.5	21	258	163	14	213	109	22	415	132
3.0	26	319	202	15	267	137	27	540	173
2.5	25	500	316	15	348	179	28	735	234
2.0	19	841	530	13	481	247	21	1074	342
1.5	10	1811	1126	9	732	370	12	1750	543

1. The random variation ($\hat{\sigma}^2$) used in this calculation equals ^{.1450}0.021019 and is based on 24 degrees of freedom.
2. The random variation ($\hat{\sigma}^2$) used in this calculation equals ^{.2027}0.04109 and is based on 21 degrees of freedom.
3. The random variation ($\hat{\sigma}^2$) used in this calculation equals ^{.3605}0.129948 and is based on 24 degrees of freedom.

SUMMARIZED RESULTS OF THE ANALYSIS

HASTELLOY-X

BEST FIT TREND LINES*

1000°F

HEAT D: $\text{Log } N = 8.37132 - 2.61229 \text{ Log } s$
HEAT E: $\text{Log } N_f^f = 8.28726 - 2.56736 \text{ Log } s$
COMBINED: $\text{Log } N_f = 8.32929 - 2.589825 \text{ Log } s$

1400°F

HEAT D: $\text{Log } N_f = 7.45134 - 1.71998 \text{ Log } s$
HEAT E: $\text{Log } N_f = 7.50419 - 2.0555 \text{ Log } s$
COMBINED: $\text{Log } N_f = 7.477765 - 1.88774 \text{ Log } s$

1600°F

HEAT D: $\text{Log } N_f = 8.23435 - 1.80178 \text{ Log } s$
HEAT E: $\text{Log } N_f = 8.22282 - 1.85988 \text{ Log } s$
COMBINED: $\text{Log } N_f = 8.229653 - 1.82545 \text{ Log } s$

* s = percent total strain. All log values are Log_e .

SUMMARIZED RESULTS OF THE ANALYSIS

HASTELLOY X

Percent Total Strain	1000°F			1400°F			1600°F		
	Effective Sample Size n_e	Expected Life (Cycles)	Lower 99/95 Limit (Cycles) ²	Effective Sample Size n_e	Expected Life (Cycles)	Lower 99/95 Limit (Cycles) ²	Effective Sample Size n_e	Expected Life (Cycles)	Lower 99/95 Limit (Cycles) ³
5.0	11	64	19	3	85	17	12	198	103
4.5	13	84	26	3	103	21	15	241	125
4.0	16	114	35	3	129	26	19	299	156
3.5	21	162	50	4	166	34	24	381	200
3.0	24	241	76	4	222	45	26	505	266
2.5	24	386	121	4	314	64	24	704	370
2.0	18	688	214	3	478	95	16	1058	552
1.5	10	1450	436	3	823	164	9	1789	915

1. The random variation ($\hat{\sigma}^2$) used in this calculation equals 0.131013 and is based on 22 degrees of freedom.
2. The random variation ($\hat{\sigma}^2$) used in this calculation equals 0.075376 and is based on 4 degrees of freedom.
3. The random variation ($\hat{\sigma}^2$) used in this calculation equals 0.0408 and is based on 23 degrees of freedom.